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16. Abstract
HEAVY is a tool that is intended for use early in the design process--concept evaluation, alternative comparison, preliminary design, control and management strategy development, component sizing, and sensitivity studies.

It allows the designer to quickly, conveniently, and economically predict the performance of a proposed drive train. It provides the capability to configure and test a proposed vehicle propulsion system at a preliminary level of detail without requiring the user to be a simulation expert. Instead, the user defines the system to be simulated using a library of predefined component models that may be connected to represent a wide variety of propulsion systems.

The models in the standard component library contain sufficient detail to be useful in predicting the performance of an electric or hybrid vehicle. They are not intended to be used as detailed design tools for a specific device, but instead to represent generic devices.

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PREFACE

The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (Public Law 94-413) authorized a Federal program of research and development designed to promote electric and hybrid vehicle technologies. The energy Research and Development Administration, now the Department of Energy (DOE), which was given the responsibility for implementing the Act, established the Electric and Hybrid Vehicle Research, Development, and Demonstration Project within the Division of Transportation Energy Conservation to manage the activities required by Public Law 94-413.

The National Aeronautics and Space Administration under an Interagency Agreement (Number DEAI01-77CS51044) was requested by ERDA (DOE) to undertake research and development of propulsion systems for electric and hybrid vehicles. The Lewis Research Center was made the responsible NASA Center for this project. The simulation program presented in this report is part of the Lewis Research Center program for propulsion system research and development for electric vehicles.

The research described in this report was conducted under Contract DEN3-151 with the National Aeronautics and Space Administration (NASA) and sponsored by the Department of Energy through an agreement with NASA.This project was conducted under sponsorship of the Energy and Aero Branch, Energy Section, NASA Lewis Research Center. Mr. Raymond Beach was the project manager.

The BCS program manager for this project was Mr. Ronald Hammond. The other major contributor to the development of HEAVY and to this document was Mr. Richard McGehee.

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1.0 INTRODUCTION

This document is the final report of NASA Contract DEN3-151, "Modification of the SIMWEST Computer Program to Simulate Hybrid and Electric Advanced Vehicle Systems (HEAVY)." This report contains:

- An overview of HEAVY that is intended to give the potential user of the program an introduction to its operation and use.
- Examples of the development of three models to serve as illustrations of the flexibility and power of the HEAVY program.
- A set of representative drive train models to illustrate the variety of simulations that may be conveniently formed from HEAVY components.

Detailed information on the use of HEAVY is contained in reference 1, "User's Guide to the Hybrid and Electric Advanced Vehicle Systems (HEAVY) Simulation."

The remainder of this section outlines the goals, approach, and scope of application of HEAVY. Section 2.0 presents a brief sketch of the use of HEAVY, emphasizing the steps that the user takes in forming and using a new HEAVY model. Sections 3.0, 4.0 and 5.0 introduce the HEAVY model generation and simulation programs using successively more complex examples. Finally, Section 6.0 contains 10 representative drive train configurations that have been modeled with HEAVY. These not only further illustrate the flexibility of HEAVY model generation, but will serve as starting points for users who wish to model similar drive trains.

Computer simulation of the performance and economy of automotive vehicle propulsion systems has received increasing interest in the past years. Simulation allows a larger set of alternative system configurations to be considered because simulations are less expensive and quicker than constructing and testing actual prototypes and simulation allows more controlled experimentation.

Increased emphasis during the last several years on energy-efficient electric and hybrid vehicles has intensified interest in vehicle simulation because:

- A wider spectrum of possible technologies and system configurations must be considered.
- The potential of new technologies must be assessed before the technologies themselves are fully developed.
- The cost of prototype development for high technology systems is high in both time and money.

Moreover, simulation must be applied at a stage in the development of a vehicle propulsion system when detailed descriptions of the components are not necessarily available. Simulation at this stage is an irreplaceable tool for concept evaluation, economic evaluation, and comparison of alternatives.

1.1 SUMMARY

HEAVY is a flexible tool for evaluating the performance of electric and hybrid vehicle propulsion systems. It allows the designer to quickly, conveniently, and economically predict the performance of a proposed drive train. It provides the capability to configure and test a proposed vehicle propulsion system at a preliminary level of detail without requiring the user to be a simulation expert. Instead, the user defines the system to be simulated using a library of predefined component models that may be connected to represent a wide variety of propulsion systems. Data and tests to be performed are also specified using English-like commands. HEAVY executes the simulation defined by the user and creates the requested output.

HEAVY has four parts:

- A library of building blocks called "standard components" which represent physical elements of a drive train — prime movers, transmissions, etc. Other standard components represent the logic used to define propulsion system controllers.

- A user-oriented model generation program which connects the standard components to form a model of a complete vehicle and drive train.

- A user-oriented simulation program which exercises the model prepared by the model generation program.

- A set of predefined models representing typical electric and hybrid vehicles.

1.2 When Should HEAVY be Used

HEAVY is a tool that is intended for use early in the design process —concept evaluation, alternative comparison, preliminary design, control and management strategy development, component sizing, and sensitivity studies. The models in the standard component library contain sufficient detail to be useful in predicting the performance of an electric or hybrid vehicle. They are not intended to be used as detailed design tools for a specific device, but instead to represent generic devices.

HEAVY does not require detailed data on the drive train being simulated — data that is not available early in the design process. Each model in the HEAVY component library contains default data which represents a typical device used in electric and hybrid vehicle drive trains. For example, the battery model represents the performance of the EV106. The user of HEAVY may vary the data used for a given device by changing a rating parameter. For example, the battery cell weight is used to scale battery capacity and performance under load. The user of HEAVY may also substitute data that is specific to a given drive train to override the default data.

HEAVY models only those characteristics which have a significant impact upon the vehicle's general performance. Propulsion systems components are modeled by their steady state performance, either by algebraic equations or by measured performance maps. Differential equations in the model represent long-term dynamics—vehicle speed and position, drive train shaft speed, etc., rather than transients such as driveshaft flexing. This type of simulation consists of a sequence of closely spaced steady state conditions rather than a true dynamic simulation. Transients are modeled in terms of

duration, energy loss, and energy transfer, but no attempt is made to model the detailed waveforms representing the actual transfer of energy.

Unlike other electric and hybrid vehicle simulations written at this level of detail, HEAVY does not deal only with power transfer. Instead, HEAVY considers torque and shaft speed or voltage and current. At each step of simulated time, HEAVY establishes a physically reasonable operating point from which to predict vehicle response during the following time step. By so doing, HEAVY is capable of estimating vehicle acceleration and predicting performance under conditions of limited resources such as battery voltage or electric machine torque.

All of the components representing prime movers contain built-in default control strategies. For example, unless otherwise instructed the d.c. shunt machine model will automatically switch from armature to field control mode at the base speed of the machine. The default control strategies may be used as they are or as starting points for development of more specific strategies.

HEAVY is economical to use so that as many variations as needed may be simulated. HEAVY achieves run time economy in four ways:

- The models in the component library are written at a level of detail consistent with application early in the design process. Therefore, they each execute very quickly.
- The high degree of user orientation reduces the number of runs wasted because of user error.
- Many cases can be performed on a single submission to the computer, thus amortizing fixed costs — model generation and run setup — over several cases.
- The FORTRAN program prepared by the model generation program is tailored to the drive train being simulated so it runs very efficiently.

1.3 Who Should Use HEAVY

HEAVY is simple to use so that the designer may use it directly rather than depending on a software expert to act as an intermediary between him and the computer. Both model generation and simulation programs use highly mnemonic statements to convey the user's requests.

HEAVY allows the user to assemble models of vehicle propulsion systems simply by specifying which library components are to be used and the order in which these components are to be connected. The components used may have large numbers of inputs, outputs, and parameters but HEAVY will, if the user does not instruct to the contrary, form all detailed connections from default assumptions. Furthermore, all input parameters specifying HEAVY components have default values. Drive train components or configurations that cannot conveniently be described by a combination of standard components may be described by conventional FORTRAN statements intermixed with normal HEAVY model generation commands.

The user of HEAVY has a set of predefined models, described in Section 6, to use either as they are or as starting points for a new model. Predefining models of specific drive train configurations gives HEAVY the convenience of a simulation with fixed vehicle models while retaining the flexibility of a modular simulation.

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2.0 OVERVIEW

HEAVY is a convenient tool for performance level simulation of electric and hybrid vehicle propulsion systems. It is valuable in:

- Performance and cost evaluation of proposed propulsion systems.
- Comparison of alternative propulsion system configurations.
- Preliminary design and propulsion system component selection.

Moreover, HEAVY places these capabilities in the hands of propulsion system analysts and designers that are not necessarily simulation or computer programming experts. Components of the HEAVY library may be assembled into propulsion systems using a special purpose computer language that requires little or no knowledge of computer programming. However, a user who so desires may enhance his HEAVY model by adding standard FORTRAN statements when needed. Furthermore, HEAVY is not limited by the existing component library. New components may be added and existing components may be modified to add more detail or to reflect improved mathematical models.

A HEAVY run has two phases:

- Model generation, in which the model described by the user's input is translated into an efficient FORTRAN subroutine. Information to verify the model is given back to the user.
- Simulation, in which the user's data and instructions are combined with the generated model to produce the desired output.

Both the HEAVY model generation and simulation programs have many user-oriented features which greatly enhance the usability of these tools. The most significant of these features are listed below.

<u>Model Generation</u>

- Simple-to-connect components — In most cases it is only necessary to name the components to which connections are to be made.

- All parameters are available to other components — This implies that any parameter may be driven as a function of other system variables.

- FORTRAN may be used in-line if needed — FORTRAN is only required when the HEAVY user wishes to perform a special function not supplied by a combination of HEAVY components.

- Lineprinter schematic of model — Comparison to the user's hand-drawn schematic is a quick and convenient model verification tool.

- Automatic naming of parameters and variables — The user need not concern himself with this tedious process.

- Data requirements list — This list is not only a convenience in preparing data for subsequent simulations, but is an additional tool for model verification.

Simulation

- All data input is in free-field format (not column-dependent) — This reduces the probability of human error in preparing data.

- Default values for unspecified parameters — The user need only supply data for items to be changed from the default.

- All output under user control — The user need only generate the output required for the specific run being made.

- Multiple simulation runs in one computer run — It is quick and convenient to run multiple cases.

- Printer/plotter output of time histories and crossplots — Plotted data gives a quick and easily visualized picture of simulation results.

2.1 MODEL GENERATION

The use of HEAVY begins when the designer prepares a block diagram or schematic of the drive train to be simulated on a special layout form which helps organize the system description in a manner compatible with HEAVY input requirements. Other blocks represent vehicle dynamics, friction brakes, driving cycle, and grade to describe the vehicle and environment in which the simulated vehicle operates. Each block on the schematic is identified with an element of the HEAVY component library. HEAVY users also have the option

to add FORTRAN statements to their model to enhance existing models, represent components not in the library, or produce special purpose outputs.

If the drive train to be simulated resembles one of the configurations stored in the library of predefined models, then the user may retrieve a predefined model from the library and use it as it is or the user may modify the predefined model to meet specific needs. Each of the predefined models is made up of conventional HEAVY model generation commands so modification of these models is simple.

Next, the HEAVY user translates the schematic into HEAVY model generation commands. These commands are elements of a special purpose computer language designed to translate the schematic into a highly mnemonic description of the model HEAVY is to generate. Each component is specified by its location on the schematic, its identity (name from the list of standard components), and its inputs.

The HEAVY model generation program translates these statements into conventional FORTRAN, generating variable names and matching the specified inputs with the outputs of the components that were specified as generating them. The lists of required inputs and generated outputs for all HEAVY components are stored on a disk file available to the model generation program.

In addition to the code for the model subroutine, the HEAVY model generation program produces three aids for the user:

- A lineprinter-drawn schematic which should mirror the user's hand-drawn schematic. The user can quickly find inconsistencies or missing connections by comparing the two.
- A list of required input data. Of course this list is helpful to the user in preparing the data for simulation. Moreover, the model generation program assumes that all unsatisfied inputs to components are fixed data items. So if unexpected items appear in the data list, the user can go back to the input statements to add omitted connections.
- A FORTRAN source listing for the model subroutine which the user may examine if FORTRAN was used in the model.

The model subroutine is compiled and linked with previously compiled code for each of the components used in the model. The result is a complete model of the user's system that is specifically tailored to the description given. Only subroutines that are needed are included.

HEAVY model generation assembles the components which describe the system to be simulated. It is only concerned with these elements and the connections which join them. Specific data — parameters, tables, initial conditions, run specifications, output requests — which are needed to complete the description of the system and the simulation to be performed are given in subsequent input. Separating model description from the data that supports it allows the same model to be used repeatedly with varying data without generating a new model for each case.

The HEAVY model generation statements describing a given drive train and vehicle may be stored for later use. The user may save models privately or, if they are of general interest, models may be added to the library of predefined configurations.

2.2 SIMULATION

The model prepared by the HEAVY model generation program is passed to the HEAVY simulation program which exercises the model according to the user's requests. Mnemonic HEAVY analysis commands such as

```
PARAMETER VALUES=(list of names & values)
INITIAL CONDITIONS=(list of names & values)
```

ease the tedious and otherwise error-prone process of data preparation. All data is in free-field (not column-dependent) format to further ease the data preparation. HEAVY supplies default values for all data for which there is a sensible default so that the user need only specify changes from the default values.

Specifications for the run to be performed — duration of simulated time, driving cycle to be used, output data content, format and frequency — are also specified with mnemonic HEAVY analysis commands. Printed output is produced in either block or column format. Time histories and crossplots may be produced on the lineprinter or on a graphics terminal.

The single command

SIMULATE

initiates the run the user has defined. Additional simulations may be performed in the same computer run. After the SIMULATE command, the user need only specify the data which is to change between runs and again command SIMULATE. Performing several cases on a run aids studies in which a group of closely related runs are to be made with only a few parameters varying between cases. Multiple cases in a run also reduces overall cost by amortizing the model generation and run setup costs over several cases.

2.3 STANDARD COMPONENT LIBRARY

The HEAVY standard component library is a collection of predefined, pretested, and compiled subroutines intended to free the HEAVY user from the necessity of building models of individual vehicle components. It is important to recognize that the capabilities of HEAVY are defined by the contents of this library and not by constraints either in the model generation or simulation programs. If it is necessary to simulate a new propulsion system component, then the only modification needed to HEAVY is the addition of a new component to the library. This principle applies not only to new components but also to the level of detail in the components. For example, a model of an electric machine must meet certain interfaces — output-shaft speed and torque and input voltage and current. The model which goes between these interfaces may be as simple or as complex as the circumstances of the study at hand require. The only difference to HEAVY is in the subroutine in the standard component library that represents this machine.

Components presently in the library are listed in Table 2-1 and briefly described in Table 2-2. These models represent:

- Common electric and mechanical drive train components and prime movers
- Vehicle dynamics, friction brakes, accessory and thermal loads to define the vehicle being simulated
- Widely used driving cycles and grades to define the environment in which the vehicle is to be tested
- A set of energy management and logic components with which to define propulsion system controllers and energy management strategies
- A set of monitoring and evaluation components to aid in assessing simulation results.

Each component in the library contains default data to represent a device typical of those used in electric and hybrid vehicles. For example, the Bozek battery model represents the EV106. The user may make small changes to component capabilities very simply. Each component is scaled with respect to an appropriate variable which may be changed to quickly adjust the size of the simulated device. For example, the battery is scaled with respect to cell weight. Changing the rating will result in cost, capacity, and terminal voltage under load being adjusted appropriately. Scaling of the components makes sensitivity studies very convenient since only one parameter need be changed between runs. The user has the option of overriding the default data to represent a different device entirely. For example, the user may present voltage-current relationships and battery characteristics to represent the ISOA battery by changing two tables and a few parameters.

Each of the components representing a prime mover or a transmission contains a default control strategy. The default strategy represents a typical approach to controlling the device. For example, the shunt field machine switches from armature to field control mode at the base speed of the machine. This strategy may be acceptable to the user or it may be acceptable for use during model development to be replaced later with a strategy more specific to a particular vehicle.

Table 2-1

STANDARD COMPONENT LIST

Energy Storage and Prime Movers		
	BA	Battery (Bozek model)
	BB	Battery (Martin model)
	EM	Synchronous Machine
	FL	Flywheel
	HE	Heat Engine
	IM	Induction Machine
	SE	Series Field Machine
	SH	Shunt Field Machine
Electrical Components		
	CH	Chopper
	IV	Inverter
Mechanical and Hydrodynamic Components		
	AT	Automatic Transmission
	CF	Continuously Variable Transmission (High Ratio)
	CL	Clutch
	CT	Continuously Variable Transmission (Low Ratio)
	DD	Differential
	FC	Fluid Coupler
	FG	Fixed Gear Ratio
	FT	Fixed Ratio Transmission
	TC	Torque Converter
Vehicle and Environment Components		
	AL	Accessory Load
	FB	Friction Brakes
	GR	Grade
	PD	EPA Driving Cycles
	TD	SAE J227a Driving Cycles
	TH	Thermal Load
	VE	Vehicle Dynamics
Energy Management and Logic Components		
	BS	Battery Switch
	CA	Current Accumulator
	CC	CVT Controller
	DI	Torque Divider
	LA	Logical "AND"
	LC	Logical "COMPARE"
	LO	Logical "OR"
	SU	Torque Summer
	SW	Two-input/One-output Switch
	SX	One-input/Two-output Switch
Monitoring and Evaluation Components		
	CO	Life Cycle Cost
	EC	Energy Consumption Summary
	HG	Histogram Generator
	PC	Purchase Cost
	ST	Statistical Analysis
	WE	Weight Evaluation

Table 2-2

HEAVY STANDARD COMPONENT DESCRIPTIONS

Energy Storage and Prime Mover Components

BA - This battery component, based upon the Bozek model, uses two tables giving terminal voltage as a function of current flow and battery state. One table is for charging and the other discharging. Battery state is calculated based on average current drawn and the Peukert relationship. Default data represents the Globe Union EV106 battery.

BB - This battery component, based upon the Martin model, uses a first-order differential equation for battery capacity and algebraic equations for state of charge and terminal voltage.

EM - The electrically commutated or synchronous machine is modeled with a set of equations derived as part of a study of electric machine models. The model is specialized to a three-phase permanent-magnet machine. Default data represents a generic machine.

FL - The HEAVY flywheel model considers bearing friction, seal, and windage loss and supplies two sets of default parameters, one representing a steel flywheel and the other a composite flywheel.

HE - This component models Stirling, Otto, diesel, and rotary engines with a performance map and engine ratings. The map is fuel consumption as a function of fractional torque and fractional speed. Ratings are peak torque, speed at peak torque, and maximum engine speed.

IM - The induction machine model uses performance maps to yield motor loss, volts per Hertz ratio, slip, and motor current. Independent variables are input frequency and volts per Hertz ratio. Default data represents an Eaton induction machine.

SE - The series D.C. machine model is based on a map of output torque as a function of speed and input voltage and a map of current as a function of torque. Default data represents a GE series machine.

SH - The separately excited or shunt field D.C. machine model uses basic machine equations along with a magnetization curve for the machine. The model will switch from armature to field control automatically or it may be controlled externally. Default data represents the machine used in the ETV-1 vehicle.

Electrical Components

CH - The chopper is modeled by a table of power loss as a function of duty cycle and current and basic current/voltage/power relation ships. Default data represents the armature chopper of the ETV-1 vehicle.

Table 2-2 (Continued)

HEAVY STANDARD COMPONENT DESCRIPTIONS

Electrical Components (Cont.)

IV - HEAVY represents an inverter with basic current/voltage/power relationships and tables of power loss and input current as a function of carrier frequency and rms current. Default data represents an Eaton inverter used to drive an induction machine.

Mechanical and Hydrodynamic Components

AT - The automatic transmission component models torque loss as a function of gear range, input torque and output speed. Default data represents a Dodge Omni transmission.

CF - This continuously variable transmission (CVT) model assumes that torque loss is a function of output torque, transmission ratio, and input shaft speed. The transmission ratio is set as part of the energy management strategy external to the transmission. Default data represents predictions of the performance of a Battelle steel V-belt transmission intended to interface with a flywheel.

CL - HEAVY models a clutch as disengaged, engaged and slipping, or engaged with no slipping. When engaged, torque loss is a function of shaft speed and torque. When disengaged, the torque loss is a function only of output rotor speed. Default data represents a lossless clutch.

CT - The second CVT component models torque loss as a function of output power. Ratio is set as part of the energy management strategy external to the transmission. Default data represents an Ai-Research twin-cavity device.

DD - HEAVY models a differential with basic torque/speed relationships and assumes that there is no wheel slippage. Torque loss is a function of input torque and shaft speed. Default data represents a generic device.

FC - HEAVY uses a table of slip as a function of torque to model a fluid coupler. Default data represents a generic device.

FG - Torque loss in a fixed gear ratio is modeled as a function of input torque and shaft speed. Default data represents a generic device.

FT - The fixed-ratio transmission component models torque loss as a function of input torque, transmission ratio, and output shaft speed. Transmission ratio is set using tables of gear ratio as a function of output torque and output shaft speed. Separate tables are used for upspeed and downspeed shifts. Default data represents a GM light pickup truck transmission. Shift schedules represent reasonable driver performance.

Table 2-2 (Continued)

HEAVY STANDARD COMPONENT DESCRIPTIONS

Mechanical and Hydrodynamic Components (Cont.)

TC - The HEAVY torque converter model uses three performance maps commonly used to describe a torque converter. These are torque ratio, capacity factor, and efficiency all as functions of speed ratio. Default data represents a generic device.

Vehicle and Environment Components

AL - The accessory load component models vehicle accessory power requirements. Default accessory load is zero.

FB - The friction brakes model simulates both the brakes and the brake application logic to accept all energy not used for regeneration. This model also provides for brake drag loss but the default drag loss is zero.

GR - The grade component allows the user to specify a grade profile as a function of distance traveled. Default grade profile is zero.

PD - The profiled driving cycle component represents the EPA urban and rural, the European FAKRA, and constant 24.6 m/s (55 mph) driving cycles. These cycles are represented as a set of velocity-time points between which the PD component uses linear interpolation. This component also allows the user to specify a driving cycle. The default is the EPA urban cycle.

TD - The target point driving cycle represents the SAE J227a driving cycles. These cycles are represented by an acceleration, cruise, coast, and brake command set. The TD component generates approximately constant power profiles between the commands. The default is schedule A. This component also allows the user to define driving cycles in the format of the J227a schedules.

TH - The thermal or engine cooling load component models the power requirement. Default thermal load is zero.

VE - The vehicle dynamics component models the physical properties of the vehicle: aerodynamic drag, rolling resistance, and velocity-dependent friction. This component generates a torque request based on the command from the driving cycle, grade, and current vehicle state. Default data represents the ETV-1 vehicle.

Energy Management and Logic Components

BS - The battery switch component allows the user to connect elements of a battery set in series/parallel combinations to provide various battery set voltages.

Table 2-2 (Continued)

HEAVY STANDARD COMPONENT DESCRIPTIONS

Energy Management and Logic Components (Cont.)

CA - The current accumulator allows the user to connect several current-drawing devices to a single source.

CC - This component sets the ratio for a continuously variable transmission within user-specified limits. Within the limits it maintains the input-shaft speed at a commanded value.

DI - The torque divider allows the user to specify priorities and weighting factors for allocation of torque to several devices.

LA - The logical "and" component represents a four-input "and" gate used in defining propulsion system controllers.

LC - The logical compare component produces a TRUE or FALSE output based upon the relative magnitudes of the two inputs.

LO - The logical "or" component represents a four-input "or" gate used in defining propulsion system controllers.

SU - The torque summer component allows the user to specify priorities and weighting factors for obtaining torque from several source devices.

SW - This switch allows one of two inputs to be connected to the output.

SX - This switch allows an input to be connected to one of two outputs.

Monitoring and Evaluation Components

CO - The life cycle cost model accepts the model of the vehicle and energy management strategy to be simulated and exercises the model over the defined schedule of yearly trips. It carefully selects portions of each daily trip and simulates vehicle performance over these segments. From these short simulations, the model extrapolates to predict energy usage and battery cycling for the entire set of trips. Maintenance and operating costs are calculated from these estimates and from distance traveled during the year using methods developed in ECONY, reference 2. Given purchase cost, yearly operating costs, and salvage value, the model summarizes life cycle cost per year and per kilometer driven.

EC - The energy consumption model produces a summary report of the energy used and regenerated during the preceding simulation run.

HG - This component prepares a histogram of a user-specified variable.

Table 2-2 (Continued)

HEAVY STANDARD COMPONENT DESCRIPTIONS

Monitoring and Evaluation Components (Cont.)

PC - The purchase cost model produces a summary report of vehicle acquisition cost. Vehicle component manufacturing or OEM costs are calculated based upon the weight estimates. Purchase cost is built up to include assembly and markup costs. This model is based upon the NASA-developed ECONY model, reference 2.

ST - The statistical analysis component calculates running values of the mean, standard deviation, maximum, and minimum of the variable to which it is connected.

WE - The weight evaluation component produces a summary report of propulsion system and vehicle weight. Propulsion system component weights are estimated based upon component ratings. Vehicle weight is built up from propulsion system weight and given payload.

2.4 PREDEFINED CONFIGURATIONS

HEAVY gives the designer the flexibility to model a wide variety of electric and hybrid drive trains. This flexibility comes from the library of standard components and the language with which to describe connections among them. However, models of specific drive train configurations may be defined and stored for later use. These models may be recalled and used as they are or may be used as starting points for a new model. For example, one of the current set of predefined models represents the GE/Chrysler ETV1 and its baseline control scheme. The HEAVY user who wishes to model a similar vehicle may copy the ETV1 model and modify the HEAVY model generation statements that define it. The user may then save the new model for later use. Models of general interest may be added to the library of predefined models.

Table 2-3 lists the 10 configurations that are currently available as predefined HEAVY models. These drive trains are described in section 6.0.

Table 2-3

PREDEFINED CONFIGURATIONS

1. Electric vehicle driven by a d.c. series machine.

2. Heat engine vehicle.

3. Electric vehicle driven by an a.c. induction machine. This model represents the drive train built by Eaton.

4. Electric vehicle driven by a d.c. shunt (separately excited) machine.

5. Electric vehicle driven by a d.c. shunt machine. This model represents the GE/Chrysler ETV1 and its baseline control strategy.

6. Electric vehicle driven by a d.c. shunt machine. This model uses battery switching to augment field control of the machine.

7. Parallel hybrid vehicle driven by a flywheel and heat engine.

8. Series hybrid with a heat engine charging batteries which drive a d.c. series machine.

9. Parallel hybrid vehicle driven by a synchronous machine and a heat engine. Mode switching and energy management are simple functions of speed.

10. Parallel hybrid vehicle driven by a synchronous machine and a heat engine. Mode switching and energy management represent the baseline approach proposed by AiResearch, reference 3.

3.0 EXAMPLE 1 - D.C. SERIES FIELD MACHINE DRIVE TRAIN

The preceding section gave an overview of HEAVY model operation, simulation and component library. However, it is easier to grasp the convenience and flexibility of HEAVY by looking at an example of modeling a simple electric vehicle propulsion system.

Figure 3-1 is a sketch of an example electric vehicle propulsion system using a battery, chopper and series field machine to drive a conventional differential. This is not intended to represent any particular vehicle, but rather to illustrate how HEAVY can keep a configuration simple and not burden the user with a mass of detail or require computer programming expertise.

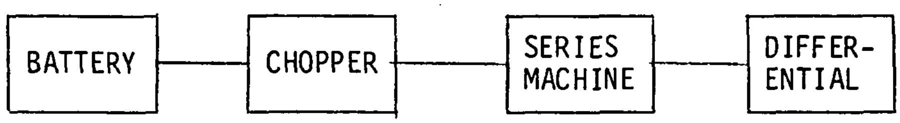

Figure 3-1. Block Diagram of Series Field Machine Drive Train

3.1 MODEL GENERATION

The first step in preparing a HEAVY model is to draw a schematic or block diagram of the system to be simulated. This schematic is usually drawn on a special form which helps the user in locating his components so that the schematic which will be drawn by the HEAVY model generation program is easy to read. Up to 10 pages of schematic may be used to define a HEAVY model. Figure 3-2 is the schematic corresponding to the sketch of the example propulsion system.

On this schematic the driveline components are even arranged to correspond to the previous sketch. Note that, in addition to the propulsion system components themselves, this schematic has a vehicle "VE," friction brakes "FB," and provision for an SAE J227a driving cycle "TD." Three evaluations components were added to request an energy consumption summary "EC," a purchase cost estimate "PC," and a vehicle weight summary "WE." This schematic shows

HEAVY SCHEMATIC LAYOUT FORM -- PAGE ___

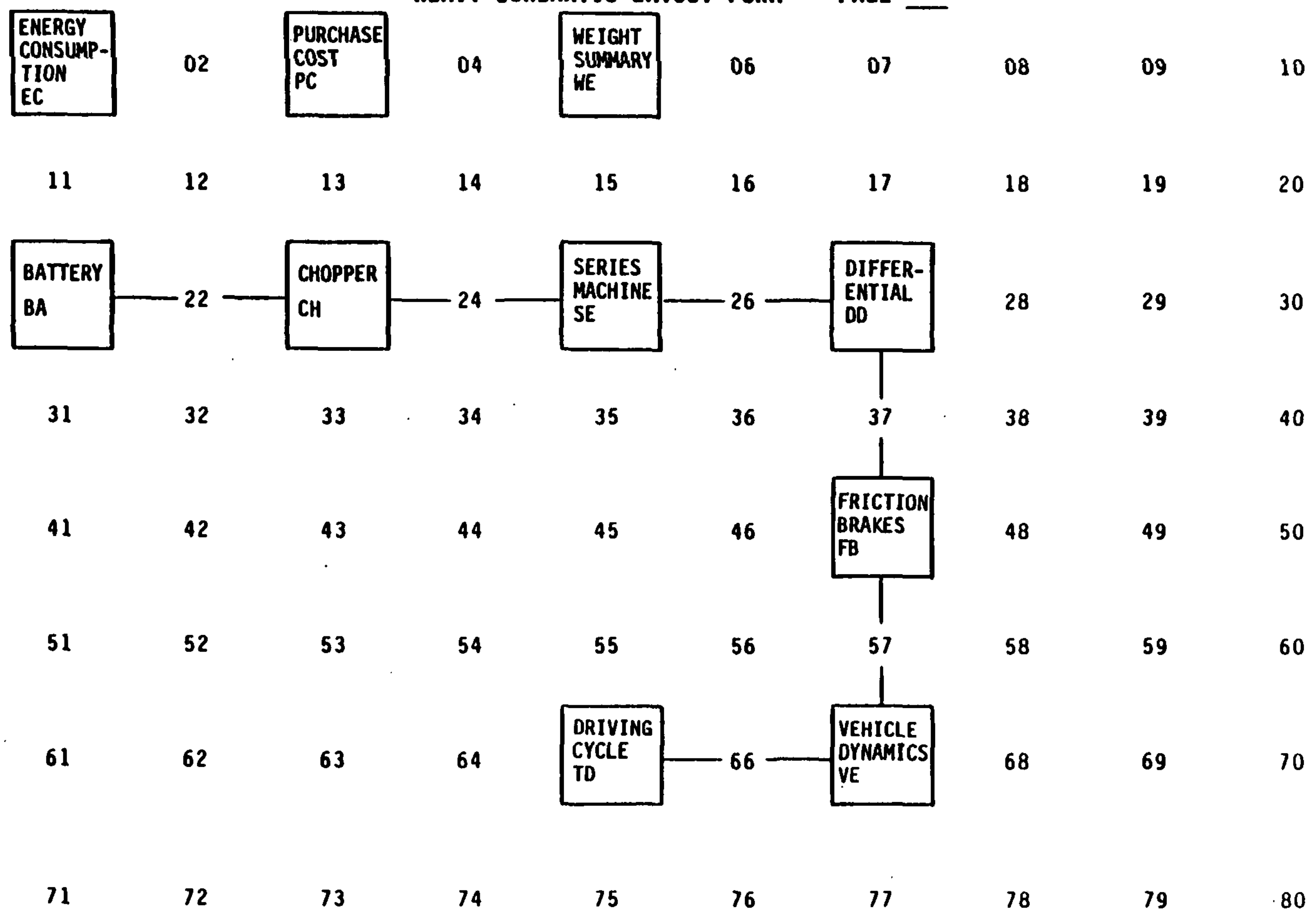

Figure 3-2. Block Diagram of Series Field Machine Drive Train and System

how the components are connected only by lines between them. Each of the possible component locations on the HEAVY schematic form is numbered. This number or location and the name of the component are the first items to be transcribed as HEAVY model generation input. For example, the first model description statement for the chopper is:

```
LOCATION = 23, CH
```

The only other information that must be specified is the identity of the components from which the component receives energy or information. In this case, the chopper receives energy from the battery. This connection is represented in a second HEAVY input statement.

```
INPUTS = BA
```

The two necessary input statements can be combined on one line as shown below. Table 3-1 shows the HEAVY model generation commands to completely describe the example simulation.

Table 3-1

MODEL GENERATION COMMANDS FOR SERIES FIELD
MACHINE DRIVE TRAIN EXAMPLE

```
MODEL DESCRIPTION = SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE
LOCATION = 21, BA
LOCATION = 23, CH     INPUTS = BA
LOCATION = 25, SE     INPUTS = CH
LOCATION = 27, DD     INPUTS = SE
LOCATION = 47, FB     INPUTS = DD
LOCATION = 67, VE     INPUTS = FB, TD
LOCATION = 65, TD
LOCATION = 01, EC
LOCATION = 03, PC
LOCATION = 05, WE
END OF MODEL
PRINT
```

The 10 simple statements which define the model to be built are preceded by a command that announces the beginning of the "MODEL DESCRIPTION" and are followed by an announcement of the "END OF MODEL" definition and a command to

"PRINT" a line printer schematic corresponding to the model as defined by the inputs. Model generation commands are free-field; that is, not column-dependent, and use commas, parentheses, three or more blanks, and equal marks interchangeably as delimiters to improve the mnemonic content of the commands.

The HEAVY model generation program accepts these simple statements, refers to the library of component input/output lists and generates the detailed connections that are required to link the component models. The names of the inputs, outputs, tables, and parameters for each HEAVY standard component are stored in a dictionary available to the model generation program. Given the user's model generation commands, the model generation program refers to this dictionary to match the names of outputs and inputs to define the details of the connections specified.

To emphasize the amount of detail that the user avoids, Figure 3-3 shows the detailed connections between the series field machine and the differential. The advantage of the HEAVY approach is now obvious. If HEAVY did not generate the detailed connections among components, then the user would be responsible for examining the component input/output lists, generating the names for each connection and preparing input statements for each--a tedious and error-prone process.

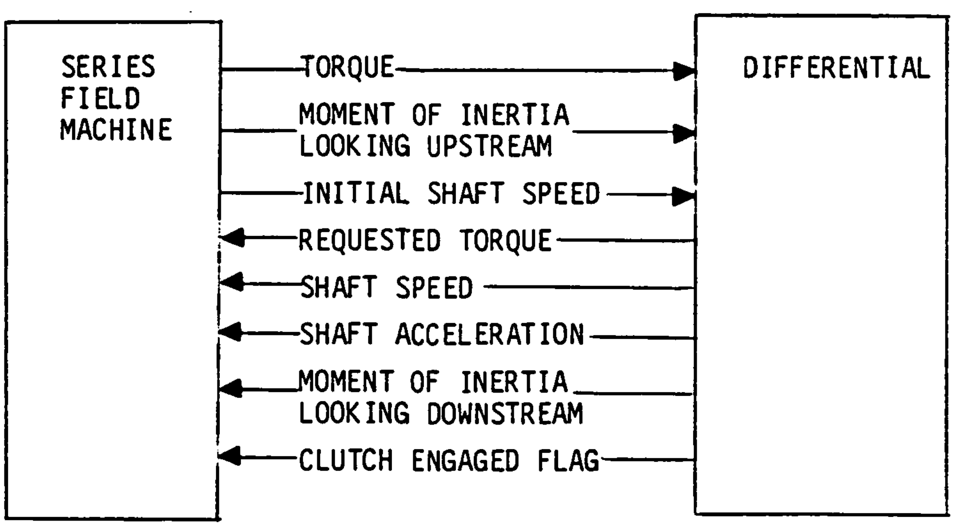

Figure 3-3. Detailed Connections Between Series Field Machine and Differential

The user is not limited to the default connections made by HEAVY. A default connection may be overridden by naming the specific variables to be connected as part of an INPUTS= statement.

After the HEAVY model generation program has formed all the detailed connections and generated the FORTRAN code which corresponds to the user's model, it prints information to aid the user in verifying the model description commands and preparing for subsequent simulation runs.

The line printer schematic requested by PRINT, Figure 3-4, should resemble the user's hand-drawn schematic. Errors in model naming and connections are usually obvious.

The list of all data (parameters and tables) required by the components in the user's system, Figure 3-5, defines the data required to complete the description of the vehicle and environment to be simulated. The user must examine this list and decide whether to accept the default tables and parameters supplied by the HEAVY standard components, change scale factors to modify defaults, or supply new data to override defaults. These lists may also be used to verify that all necessary connections have been made. The HEAVY model generation program assumes that any component input that is not connected to the output of another component is to be considered a parameter. If the name of a needed input, say the battery voltage input to a chopper, appears on the list of parameter names, the user must inspect the model generation commands for a missing connection specification.

The listing of the FORTRAN subroutine corresponding to the user's system, Figure 3-6, is needed by HEAVY users that have included FORTRAN in their model description to verify that their FORTRAN input is correct. After the nonexecutable statements which specify all the parameter, variable, table, and state names for the user's model the FORTRAN consists of a sequence of CALLs to subroutines each of which represent a single standard component.

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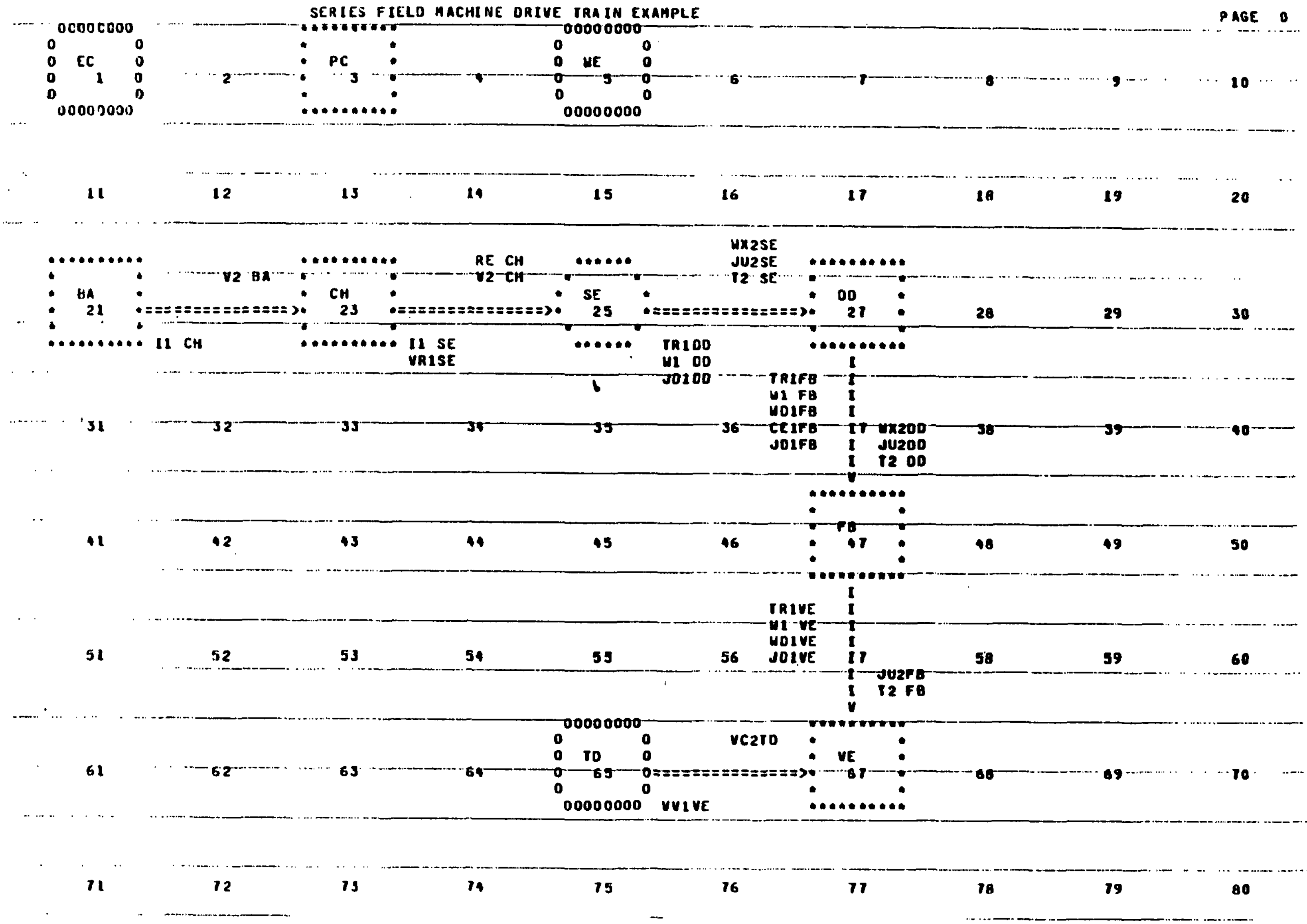

Figure 3-4. Lineprinter Schematic of Series Field Machine Drive Train Example

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SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE

THIS MODEL CONTAINS 10 COMPONENTS
WITH 11 TABLES 120 PARAMETERS 7 STATES AND 62 VARIABLES

INPUT DATA REQUIREMENTS LIST

TABLES REQUIRED

COMPONENT NAME	TABLE NAME	NO. INDEP. VARIABLES	MAX. DATA ALLOWED
BA	VC BA	2	71
BA	VD BA	2	95
CH	PL CH	2	77
CH	CF CH	1	14
SE	TI SE	1	16
SE	TW SE	2	147
SE	TIRSE	1	27
SE	TWRSE	2	147
DD	TLPDD	2	134
FB	TL FB	1	27
TD	VC TD	1	27

PARAMETERS REQUIRED

COMPONENT NAME	PARAMETER NAME
BA	SO2BA
BA	VO BA
BA	V1 BA
BA	CA BA
BA	NC BA
BA	WC BA
BA	CE BA
BA	CC BA
BA	PK1BA
BA	PK2BA
BA	PKXBA
BA	RI BA
BA	AN BA
BA	BN BA
BA	CN BA
BA	DN BA
BA	PS BA
CH	D CH
CH	SD CH
CH	IR CH

Figure 3-5. Data Requirements List for Series Field Machine Drive Train Example

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```
      SUBROUTINE EQMO(TIME,TSTEP,INDP)
C
C          SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE
C
C --->          THIS SUBROUTINE WAS PREPARED BY THE EASY PRECOMPILER
C                              USING  HYBRID     COMPONENTS
      COMMON/CXDOT/XDOT(    7)/CINT/INX(    7)
      COMMON/CSIMUL/DUM(6),TINC,THAX,DUM2(6)
      COMMON/CIMPL/IMPL,ICNT,ITEST/COVRLY/ADUM(3),CPUSEC
      COMMON/COST/CCO(9)
C --->          STATE VARIABLES
      COMMON /CX/EO2BA   ,ER2BA   ,AT2BA   ,AR2BA   ,EN2FB   ,PV1VE   ,VV1VE
C --->          VARIABLES
      COMMON /CV/V2 BA   ,ST2BA   ,BW2BA   ,BC2BA   ,AN BA   ,BI BA   ,PO BA
     X,CR BA   ,PROBA   ,V2 CH   ,I1 CH   ,DC CH   ,EF CH   ,WT CH   ,CO CH   ,
     XFC CH   ,RE CH   ,T2 SE   ,JU2SE   ,WX2SE   ,I1 SE   ,VR1SE   ,CO SE   ,
     XWT SE   ,EF SE   ,T2 DD   ,JU2DD   ,WX2DD   ,TR1DD   ,W1 DD   ,WD1DD   ,
     XCE1DD   ,JD1DD   ,CO DD   ,WT DD   ,EF DD   ,T2 FB   ,JU2FB   ,WX2FB   ,
     XTR1FB   ,W1 FB   ,WD1FB   ,CE1FB   ,JD1FB   ,T8 FB   ,TR1VE   ,W1 VE   ,
     XWD1VE   ,JD1VE   ,AV VE   ,WT VE   ,GW VE   ,WC VE   ,WS VE   ,WE VE   ,
     XWF VE   ,VC2TD   ,TO TD   ,VCSTD   ,X  EC   ,X  PC   ,X  WE
      REAL I1 CH   ,JU2SE   ,I1 SE   ,JU2DD   ,JD1DD   ,JU2FB   ,JD1FB   ,
     XJD1VE
C --->          PARAMETERS
      COMMON /CP/SO2BA   ,VO BA   ,W1 BA   ,CA BA   ,NC BA   ,WC BA   ,CE BA
     X,CC BA   ,PK1BA   ,PK2BA   ,PKXBA   ,RI BA   ,AN BA   ,BN BA   ,CN BA   ,
     XDN BA   ,PS BA   ,D  CH   ,SD CH   ,IR CH   ,WI CH   ,C  CH   ,AN CH   ,
     XBN CH   ,CN CH   ,RP CH   ,FWTCH   ,FLOCH   ,DCLCH   ,C  SE   ,JI SE   ,
     XWI SE   ,AN SE   ,BN SE   ,CN SE   ,DN SE   ,EN SE   ,HN SE   ,WO SE   ,
     XRT SE   ,RP SE   ,FWTSE   ,FLOSE   ,C  DD   ,JI DD   ,WI DD   ,RT DD   ,
     XD  DD   ,TN DD   ,WN DD   ,RP DD   ,FWTDD   ,FLODD   ,CE2FB   ,JI FB   ,
     XAN FB   ,BF FB   ,GR1VE   ,RHOVE   ,CD VE   ,A  VE   ,RW VE   ,WTOVE   ,
     XK1 VE   ,K2 VE   ,G  VE   ,JW VE   ,WP VE   ,PM VE   ,PT VE   ,MF VE   ,
     XAF VE   ,WF1VE   ,WF2VE   ,WF3VE   ,WF4VE   ,WF5VE   ,WF6VE   ,WF7VE   ,
     XWF8VE   ,WF9VE   ,S  TD   ,TI TD   ,C1 PC   ,C2 PC   ,C3 PC   ,C4 PC   ,
     XC5 PC   ,C6 PC   ,C7 PC   ,C8 PC   ,C9 PC   ,C10PC   ,C11PC   ,C12PC   ,
     XC13PC   ,C14PC   ,C15PC   ,C16PC   ,C17PC   ,C18PC   ,C19PC   ,C20PC   ,
     XC21PC   ,C22PC   ,C23PC   ,C24PC   ,C25PC   ,C26PC   ,C27PC   ,C28PC   ,
     XC29PC   ,C30PC   ,C31PC   ,C32PC   ,C33PC   ,C34PC   ,CYCLES  ,DLINES  ,
     XRESET
      REAL NC BA   ,IR CH   ,JI SE   ,JI DD   ,JI FB   ,K1 VE   ,K2 VE   ,
     XJW VE   ,MF VE
C --->          TABLES
      COMMON/CTABLE/ VC BA   ( 74),VO BA   ( 98),PL CH   ( 80),
     XCF CH   ( 17),TI SE   ( 19),TW SE   (150),TIRSE   ( 30),TWRSE   (150),
     XTLPDD   (137),TL FB   ( 30),VC TD   ( 30)
C --->                         MODEL EQUATIONS
      COMMON/CREVRS/IREVRS,IFP
      COMMON/CPFLAG/PFLAG,ITINC
      IFP=1
      IF(CPUS.EQ.CPUSEC)GO TO 9000
      IF(CYCLES.EQ.0.99999) CYCLES=10.
      ITEST=0
      IF(RESET.GT.0.)ITEST=1
      CPUS=CPUSEC
      ICNT=0
      IMPL=0
```

Figure 3-6. FORTRAN Listing of Series Field Machine Drive Train Example

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```
  9000 CONTINUE
       IF(ITINC.NE.1) GO TO 9900
       IREVRS=1
C
C ===== CALL MODULES IN REVERSE ORDER =========
C
C
C                    COMPONENT  WE
C
       CALL WE(X  WE  )
C
C                    COMPONENT  PC
C
       CALL PC(X  PC  ,C1 PC  ,C2 PC  ,C3 PC  ,C4 PC  ,C5 PC  ,C6 PC  ,
      XC7 PC  ,C8 PC  ,C9 PC  ,C10PC  ,C11PC  ,C12PC  ,C13PC  ,C14PC  ,
      XC15PC  ,C16PC  ,C17PC  ,C18PC  ,C19PC  ,C20PC  ,C21PC  ,C22PC  ,
      XC23PC  ,C24PC  ,C25PC  ,C26PC  ,C27PC  ,C28PC  ,C29PC  ,C30PC  ,
      XC31PC  ,C32PC  ,C33PC  ,C34PC  )
C
C                    COMPONENT  EC
C
       CALL EC(X  EC  )
C
C                    COMPONENT  TD
C
       CALL TD(VC TD  ,VC2TD  ,TO TD  ,VCSTD  ,VV1VE  ,S  TD  ,TI TD  )
C
C                    COMPONENT  VE
C
       CALL VE(TR1VE  ,W1 VE  ,WD1VE  ,JD1VE  ,PV1VE  ,XDOT(  0),INX(  0)
      X,VV1VE  ,XDOT(  0),INX(  0),AV  VE  ,WT  VE  ,GW  VE  ,WC  VE  ,
      XWS VE  ,WE  VE  ,WF  VE  ,T2 FB  ,JU2FB  ,GR1VE  ,VC2TD  ,RHOVE  ,
      XCD VE  ,A   VE  ,RW  VE  ,WTOVE  ,K1  VE  ,K2  VE  ,G   VE  ,JW  VE  ,
      XWP VE  ,PM  VE  ,PT  VE  ,MF  VE  ,AF  VE  ,WF1VE  ,WF2VE  ,WF3VE  ,
      XWF4VE  ,WF5VE  ,WF6VE  ,WF7VE  ,WF8VE  ,WF9VE  )
C
C                    COMPONENT  FB
C
       CALL FB(TL FB  ,T2 FB  ,JU2FB  ,WX2FB  ,EN2FB  ,XDOT(  0),INX(  0)
      X,TR1FB  ,W1 FB  ,WD1FB  ,CE1FB  ,JD1FB  ,TB FB  ,T2 DD  ,JU2DD  ,
      XWX2DD  ,TR1VE  ,W1 VE  ,WD1VE  ,CE2FB  ,JD1VE  ,JI FB  ,AN FB  ,
      XBF FB  )
C
C                    COMPONENT  DD
C
       CALL DD(TLPDD  ,T2 DD  ,JU2DD  ,WX2DD  ,TR1DD  ,W1 DD  ,WD1DD  ,
      XCE1DD  ,JD1DD  ,CO DD  ,WT DD  ,EF DD  ,T2 SE  ,JU2SE  ,WX2SE  ,
      XTR1FB  ,W1 FB  ,WD1FB  ,CE1FB  ,JD1FB  ,C  DD  ,JI DD  ,WI DD  ,
      XRT DD  ,D  DD  ,TN DD  ,WN DD  ,RP DD  ,FWTDD  ,FLODD  )
C
C                    COMPONENT  SE
C
       CALL SE(TI SE  ,TW SE  ,TIRSE  ,TWRSE  ,T2 SE  ,JU2SE  ,WX2SE  ,
      XI1 SE  ,VR1SE  ,CO SE  ,WT SE  ,EF SE  ,V2 CH  ,TR1DD  ,W1 DD  ,
      XJD1DD  ,C  SE  ,JI SE  ,WI SE  ,AN SE  ,BN SE  ,CN SE  ,DN SE  ,
      XEN SE  ,HN SE  ,RE CH  ,WO SE  ,RT SE  ,RP SE  ,FWTSE  ,FLOSE  )
C
```

Figure 3-6. FORTRAN Listing of Series Field Machine Drive Train Example (Continued)

3.2 SIMULATION

After verifying that the model description is correct and complete, the user is ready to prepare the data and commands for the simulation runs to be made. HEAVY has default values for all parameters so the user need only specify the data items that differ from the default. When it is necessary to override a default parameter value, the user merely writes:

```
PARAMETER VALUES   Parameter Name = value
```

If several parameters are to be changed, they may be changed in a single command by separating the changes by commas. In the example system, suppose that the vehicle is to be run over a single J227a Schedule D driving cycle. The user refers to the description of the TD component to find the parameter name and value, then writes

```
PARAMETER VALUES   S TD=4.
```

The user may specify initial conditions if desired, but all state variables will be initialized to zero, so only those with nonzero initial conditions need be specified. For example, it might be required to determine the maximum range of a given vehicle at a constant speed without simulating the acceleration to that speed. To initialize the velocity to the given speed, the user would consult list of names generated for the vehicle component and then write:

```
INITIAL CONDITIONS   VV1VE = value
```

Printed output is requested using a simple command:

```
PRINT VARIABLES   VV1VE,name,name ....
```

And the frequency (time between printout) of printed output is controlled by a similarly mnemonic command.

PRATE = n   where n is the number of integration steps between printouts.

Plotted output is requested by defining "DISPLAYS," each of which may contain up to six plots. Up to five displays may be defined using a command like:

DISPLAY1, VV1VE, VS, TIME, ...

The first plot in display number 1 would be a plot of VV1VE (velocity) versus time and the other plots in the display would be similarly defined. Output variable names are found in the standard component descriptions.

After all data and run specifications are complete, the user gives one final command:

SIMULATE

to initiate the run. If more than one case is to be performed on a given run, then the user need only define the data, initial conditions and run specifications which are to change between cases, and again command SIMULATE.

To emphasize again the simplicity of performing a HEAVY run, Table 3-2 is the data necessary to run the example system over a single Schedule D driving cycle.

Table 3-2

ANALYSIS COMMANDS FOR SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE

TITLE = SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE	TITLE specifies a title which will appear on the printed and plotted output.
PARAMETER VALUES S TD = 4	PARAMETER VALUES announces that a following set of names and values will override default data items.
TMAX = 122.	TMAX sets the maximum value of simulated time for the run to be made.
TINC = 0.5	TINC sets the integration step for the run to be made.
PRINTER PLOTS	PRINTER PLOTS specifies that plots are to be made on the run being defined.
PRINT CONTROL = 3	PRINT CONTROL allows the user to choose from six output formats for his printed output.
DISPLAY1 VV1VE, VS, TIME DISPLAY2 I1 CH, VS, TIME T2 SE, VS, TIME DISPLAY3 EF CH, VS, TIME EF SE, VS, TIME EF DD, VS, TIME	Each DISPLAY command allows the user to define up to four time histories or crossplots to be made.
SIMULATE	SIMULATE announces that all specifications are complete and that the run may begin.

3.3 RESULTS

Figures 3-7, 3-8, and 3-9 are the plots produced by the DISPLAY commands in Table 3-2. These show vehicle velocity (VV1VE), chopper input current (I1CH), series field machine torque (T2SE), and the efficiencies of the chopper, series field machine, and differential (EF CH, EF SE and EF DD) as functions of time. Any variable in the model may be plotted as a time history or as a crossplot.

Figures 3-10, 3-11, and 3-12 are the user change of CERs and weights outputs of the three summary components "EC," "PC," and "WE."

This example shows that only a few commands are necessary to define a drive train and vehicle and to perform a simulation to obtain both dynamic and summarized information on vehicle performance.

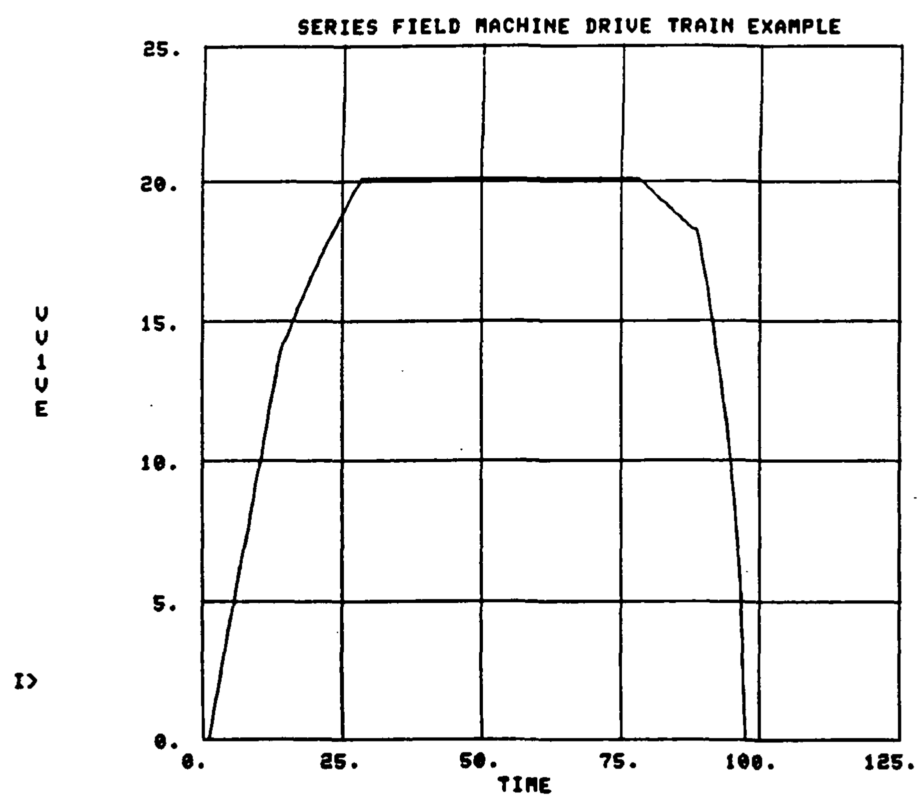

Figure 3-7. D-Cycle Velocity Profile of Series Field Machine Drive Train Example

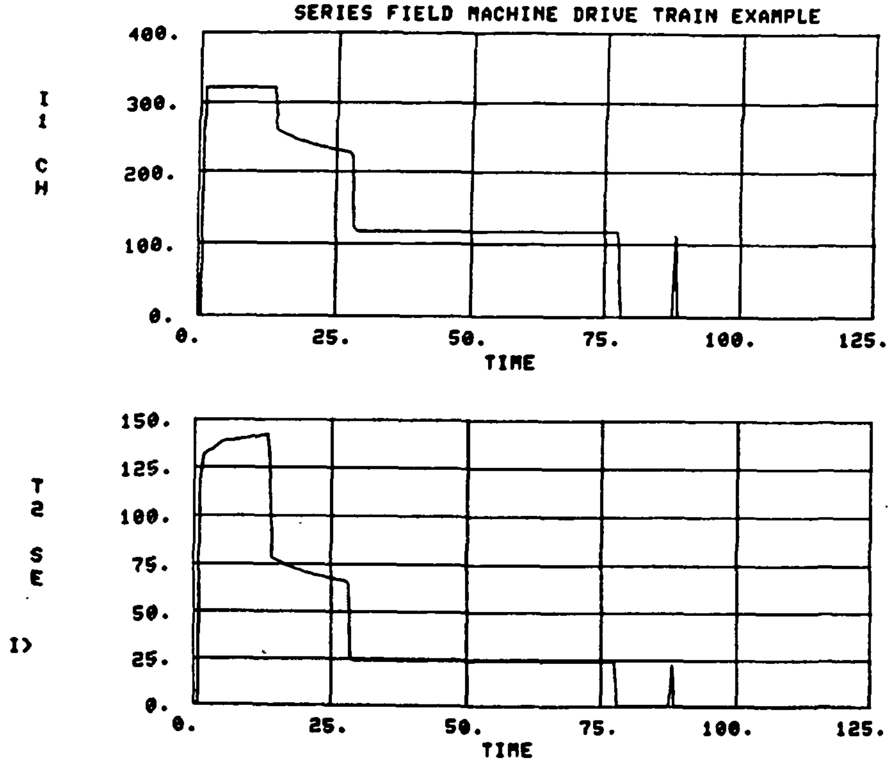

Figure 3-8. D-Cycle Current and Torque Profiles of Series Field Machine Drive Train Example

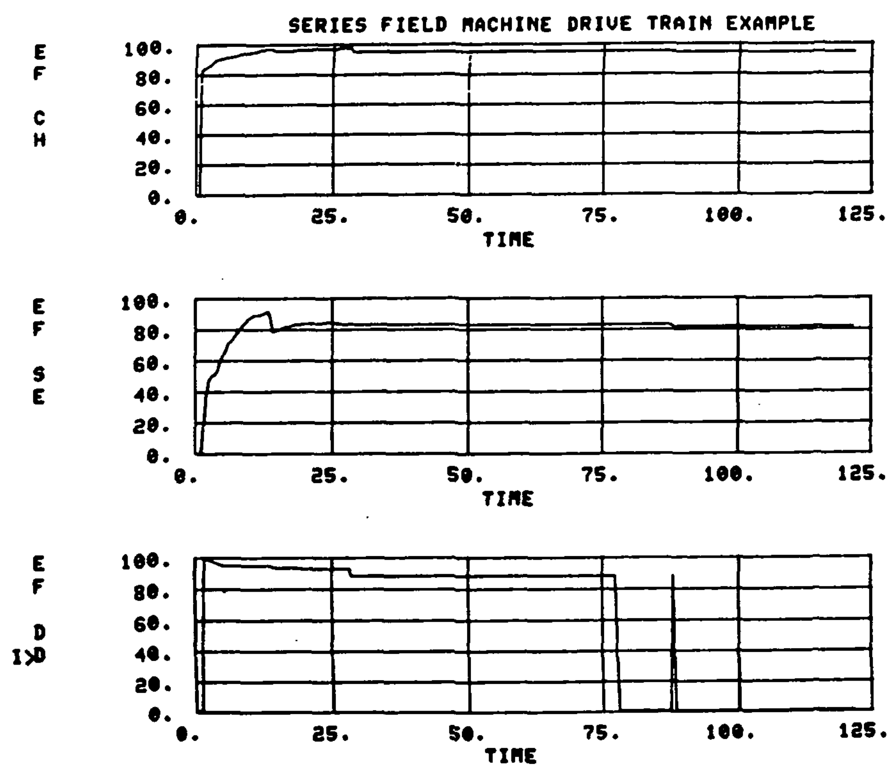

Figure 3-9. Efficiency Profiles of Series Field Machine Drive Train Example

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ENERGY CONSUMPTION EVALUATION

ENERGY DELIVERED BY BATTERY (KW-HRS)	.3776483
ENERGY REGENERATED TO BATTERY (KW-HRS)	0.
NET BATTERY ENERGY (KW-HRS)	.3776483
ENERGY DELIVERED BY FLYWHEEL (KW-HRS)	0.
ENERGY REGENERATED TO FLYWHEEL (KW-HRS)	0.
NET FLYWHEEL ENERGY (KW-HRS)	0.
ENERGY DELIVERED BY HEAT ENGINE (KW-HRS)	0.
WEIGHT OF FUEL USED (KILOGRAMS)	0.
FINAL STATE OF CHARGE OF THE BATTERY	.9697972
FINAL STATE OF CHARGE OF THE FLYWHEEL	0.
ENERGY ABSORBED BY BRAKES (KW-HRS)	.7226139E-01

Figure 3-10. Energy Consumption Summary for Series Field Machine Drive Train Example

PURCHASE COST MODEL (DOLLARS)

				PERCENT OF PURCHASE PRICE
PROPULSION SYSTEM COST			1272.38	15.10
	COMPONENT	COST		
	CH	512.71		6.08
	SE	495.00		5.87
	OD	149.38		1.77
	MISC.	115.29		1.37
VEHICLE COST			1643.10	19.50
	COMPONENT	COST		
	FRAME AND BODY	319.49		3.79
	SUSPENSION AND BRAKES	412.56		4.89
	FENDERS AND PANELS	86.79		1.03
	STEERING	47.79		.57
	WHEELS AND TIRES	220.07		2.61
	BODY SHELL	556.41		6.60
ASSEMBLY COST			+ 176.90	2.10
DRY COST			3092.38	36.69
BATTERY COST			992.63	11.78
MARKUP:	DRY COST		4045.50	48.00
	BATTERY COST		+ 297.79	3.53
PURCHASE PRICE			8428.30	

Figure 3-11. Purchase Cost Evaluation for Series Field Machine Drive Train Example

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WEIGHT EVALUATION (KILOGRAMS)

			PERCENT OF GROSS WEIGHT
PROPULSION SYSTEM WEIGHT		186.8308	10.95
COMPONENT	WEIGHT		
CH	39.5000		2.31
SE	100.0000		5.86
DD	35.0000		2.05
MISC.	12.3308		.72
BATTERY WEIGHT		530.8200	31.11
STRUCTURE WEIGHT		392.4477	23.00
COMPONENT	WEIGHT		
FRAME AND BODY	250.3817		14.67
SUSPENSION AND BRAKES	142.0661		8.33
FIXED WEIGHT		324.1960	19.00
COMPONENT	WEIGHT		
FENDERS AND PANELS	50.5746		2.96
STEERING	16.2098		.95
WHEELS AND TIRES	65.8118		3.86
BODY SHELL	191.5998		11.23
MAXIMUM FUEL WEIGHT		+ 0.0000	0.00
CURB WEIGHT		1434.2945	84.06
MAXIMUM PAYLOAD		+ 272.0000	15.94
GROSS WEIGHT		1706.2945	
TEST FUEL WEIGHT		0.0000	
TEST PAYLOAD		136.0000	
TEST WEIGHT		1570.2945	

Figure 3-12. Weight Summary for Series Field Machine Drive Train Example

4.0 EXAMPLE 2 - GE/CHRYSLER ETV1

This example illustrates how a HEAVY model may be tailored to represent a specific vehicle and test environment. It also introduces the ability to override default connections among components. Figure 4-1 is a block diagram of the drive train and baseline motor controller of the GE/Chrysler ETV1 vehicle. The controller contains switching and logic to force the shunt field machine into field control mode and bypass the armature circuit chopper when the armature chopper duty cycle approaches 1.0 or when the machine is above base speed.

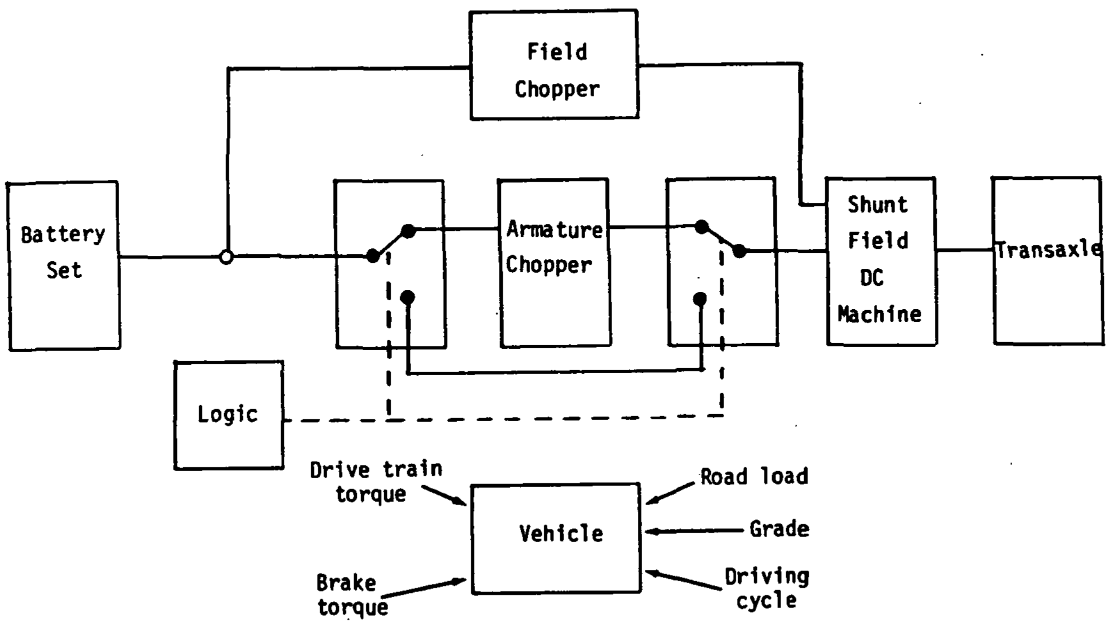


Figure 4-1. Block Diagram of ETV1 Drive Train

4.1 MODEL GENERATION

Figure 4-2 shows the two pages of HEAVY schematic that correspond to the block diagram and the surrounding vehicle and environment components which complete the description of the physical system to be simulated.

Table 4-1 shows the 19 HEAVY model generation commands that define the ETV1 model shown on the schematic. In most cases the inputs are specified merely by mentioning the name of the components which precede the component being

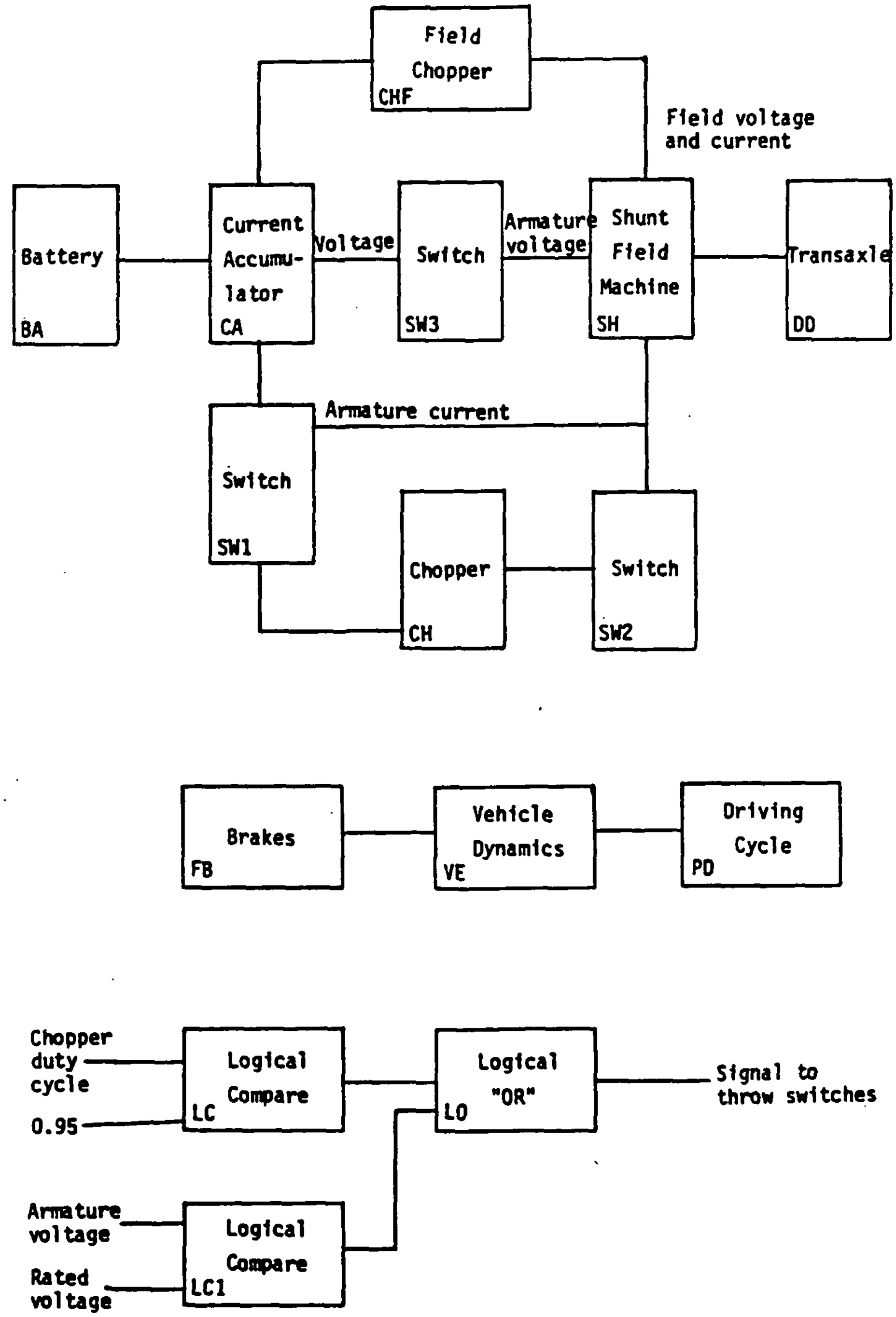


Figure 4-2. HEAVY Schematic for ETV1 Vehicle

defined. However, the HEAVY model generation program gives the user the flexibility to override default connections for special purposes such as connecting the motor controller into the armature circuit of the ETV1 model. Specific connections are made by adding modifying phrases to the INPUTS= commands affected. The HEAVY user's guide contains the details of making specific connections between standard components.

The 17 components described in the ETV1 model of Table 4-1 specify 7 states, 12 tables, 90 variables and 101 parameters. If the model generation program did not form the detailed connections the user would be responsible for the tedious and error-prone task of referring to a dictionary to look up input and output names, forming unique FORTRAN names from them, and inserting these names into CALLs to the subroutines that represent the standard components. To save space the model verification outputs — schematic, data requirements lists, and FORTRAN listing —are not reproduced here.

Table 4-1

MODEL GENERATION COMMANDS TO DEFINE THE ETV1

```
MODEL DESCRIPTION=ETV1 DRIVETRAIN, VEHICLE, CONTROLLER
LOCATION=002   BA
LOCATION=032   CA    INPUTS=BA,SW1(V01=I,2)
LOCATION=042   SW1   INPUTS=CHA(I,1=VA1),SH(I,1=VB1),LO(TRU=SWI)
LOCATION=075   CHA   INPUTS=CA(2=1),SW2(V01=I,2),SH(VR,1=VR,2)
LOCATION=037   CHF   INPUTS=CA(3=1)
LOCATION=057   SW2   INPUTS=SH(I,1=VA1),LO(TRU=SWI)
LOCATION=014   SW3   INPUTS=CHA(V,2=VA1),CA(V,2=VB1),LO(TRU=SWI)
LOCATION=134   LO    INPUTS=LC(TRU=L1),LC1(TRU=L2)
LOCATION=132   LC1   INPUTS=SH(VR,1=L1)
LOCATION=102   LC    INPUTS=CHA(DC=L1)
LOCATION=019   SH    INPUTS=SW3(V01=V,1),CHF(2=3),CHA(RE=RE)
LOCATION=161   DD    INPUTS=SH
LOCATION=163   FB    INPUTS=DD
LOCATION=165   VE    INPUTS=FB,PD
LOCATION=167   PD
LOCATION=105   WE
LOCATION=107   EC
END OF MODEL
```

4.2 SIMULATION

After verifying that his model generation commands are complete and correct, the user prepares a set of HEAVY analysis commands to describe:

- Changes from default data supplied by the standard components
- Frequency, content, and format of printed output
- Frequency and content of plotted output
- Duration of simulated time for which the run will be made

Table 4-2 shows the HEAVY analysis commands to drive the ETV1 model over a driving cycle to duplicate experimental results from NASA's Road Load Simulator. Many other analysis commands are described in the HEAVY user's guide. New commands are annotated to the right.

4.3 COMPARISON WITH ROAD LOAD SIMULATOR RESULTS

The Road Load Simulator (RLS) facility at the NASA Lewis Research Center was used to test and evaluate the ETV1 propulsion system. The propulsion system was instrumented and tests were conducted to characterize the drive under steady state conditions for all operating modes. The propulsion system was also tested for transient performance over the SAE J227a, schedule D cycle and under full throttle acceleration. The transient tests for the D cycle will be used here to compare simulated and laboratory performance of the ETV1 propulsion system.

Tables 4-1 and 4-2 show the model generation commands and analysis commands to define the ETV1 model and its controller. The analysis commands include PARAMETER VALUES to reproduce the exact test parameters and velocity profile used in the RLS facility. Battery characteristics were for the default EV106.

Table 4-2

ANALYSIS COMMAND FOR THE ETV1 SIMULATION

```
TITLE=ETV1 DRIVE TRAIN, VEHICLE AND CONTROLLER
PARAMETER VALUES
IR CHF=20.,D  DD=5.48
L2 LC1=96,L2 LC=0.95,VB1SW2=0.
S  PD=0.

TABLE=VC PD(50)
 0.      1.     2.     3.     4.     5.
 6.      7.     8.     9.    10.    11.
12.     13.    14.    15.    16.    17.
18.     19.    20.    21.    22.    23.
24.     25.    26     27.    28.    78.
79.     80.    81.    82.    83.    84.
85.     86.    87.    88.    89.    90.
91.     92.    93.    94.    95.    96.
97.   122.
00.00  01.14  02.29  03.43  04.58  05.72
06.87  07.95  08.98  09.94  10.85  11.71
12.52  13.29  14.01  14.69  15.32  15.91
16.47  16.99  17.48  17.92  18.33  18.71
19.05  19.36  19.64  19.89  20.10  20.10
19.46  18.92  18.48  18.06  17.67  17.31
16.99  15.57  14.16  12.74  11.32  09.91
08.49  07.08  05.66  04.25  02.83  01.42
00.00  00.00
```

TABLE announces that following lines contain data to override a default table, in this case the velocity/time profile for the driving cycle to be simulated. The first block of data is values of the independent variable, time, and the second block is values of the dependent variable, velocity (m/s).

```
PRINT CONTROL=5.

DEFINE STATES
6=POSIT,7=VELOC
DEFINE RATES   7=ACCEL
DEFINE VARIABLES
14=AMPS,40=TORQUE,24=FIELDV,16=ARM V,
59=SHAFTW,2=AMPHRS
```

DEFINE STATES, RATES and VARIABLES allow the user to associate .names he chooses with items named by the model generation program.

```
PRINT VARIABLES=POSIT,VELOC,ACCEL,TORQUE,
                AMPHRS,AMPS
```

PRINT VARIABLES names the items to be included in the printed output.

```
DISPLAY1,VELOC,VS,TIME
         VC2PD,VS,TIME
DISPLAY2,AMPS,VS,TIME
         AMPHRS,VS,TIME
DISPLAY3,EF SH,VS,TIME
DISPLAY4,EF DD,VS,TIME
DISPLAY5,EF CHA,VS,TIME
DISPLAY6,T2 SH,VS,TIME
PRINTER PLOTS
OUTRATE=2.

TMAX=122.
TINC=0.5
SIMULATE
```

OUTRATE (output rate) states the number of integration steps that will elapse between addition of points to the plots to be made.

Table 4-3 is a summary of simulated and measured energy consumption for acceleration, cruise, coast, and braking. The values predicted by HEAVY agree very well with RLS measurements.

Table 4-3

COMPARISON OF ENERGY CONSUMPTION
DURING SAE J227a SCHEDULE D

	Energy (Wh)	
	HEAVY	RLS
Acceleration	71.6	71.6
Cruise	120.9	131.4
Coast	19.8	24.3
Braking	47.0	31.9
Total	259.3	259.2

Figure 4-3 through 4-8 are computer-graphic plots of RLS and of HEAVY results placed side by side for direct comparison. RLS results were plotted directly from information provided by the RLS interactive data reduction system. HEAVY results were plotted interactively from the version of HEAVY available on the BCS MAINSTREAM EKS timesharing service. These figures were selected from the many measurements available from RLS results to examine system performance at points throughout the drive train. The RLS results are at the top of each figure and the HEAVY results below. In all cases the shape and magnitude of the plots agree very well.

This example shows that HEAVY standard components may be assembled quickly to represent the configuration of a specific drive train, vehicle, and operating environment. Default control strategies built into these components allow quick testing of generic drive trains. Adding a few logic components from the HEAVY library allows simulation of a specific control strategy. Changing a few default parameters allows the simulation to be tailored to match a specific set of test inputs. The excellent agreement of simulated and measured results shows that the HEAVY simulation responses are quite realistic.

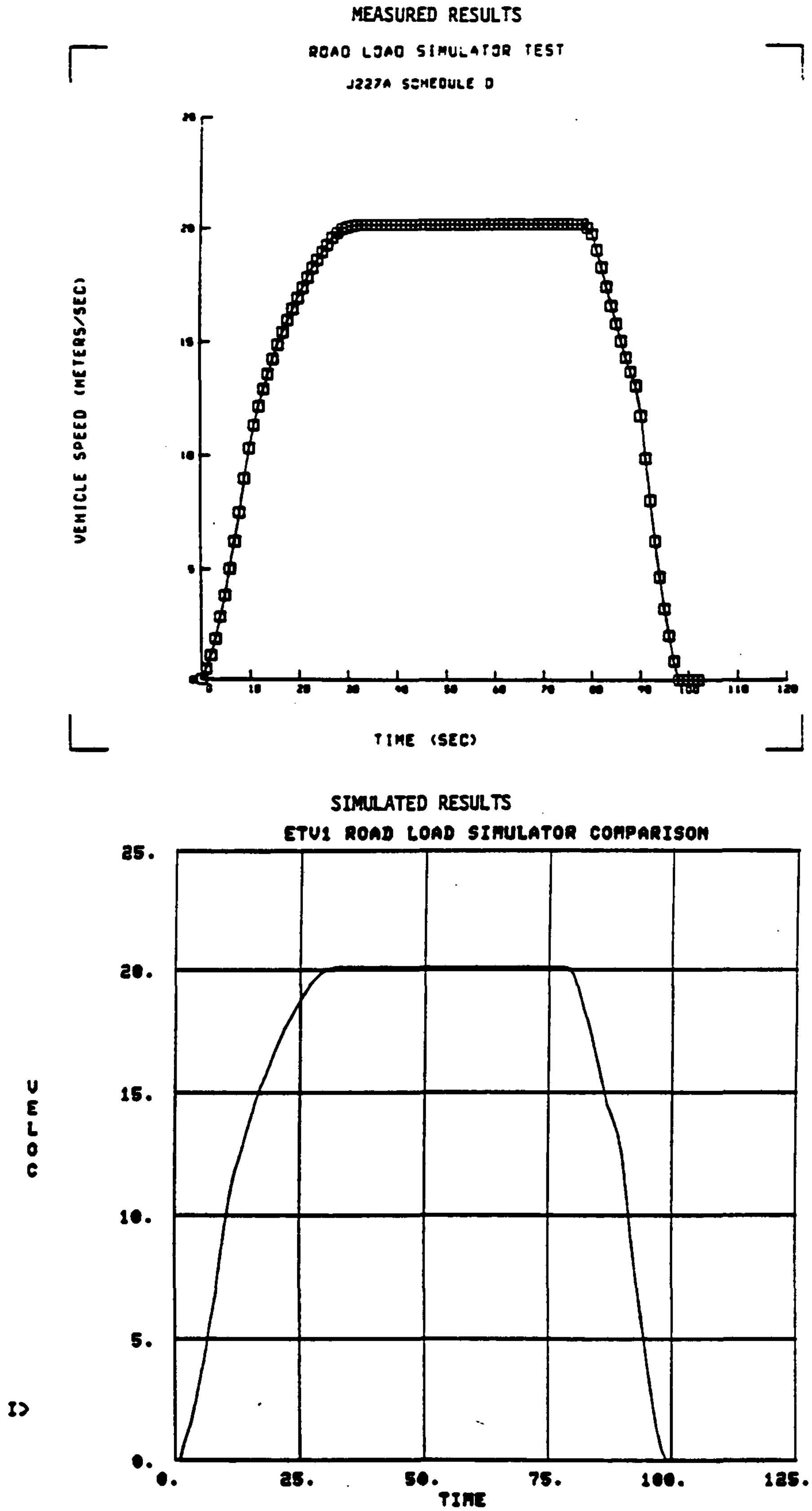
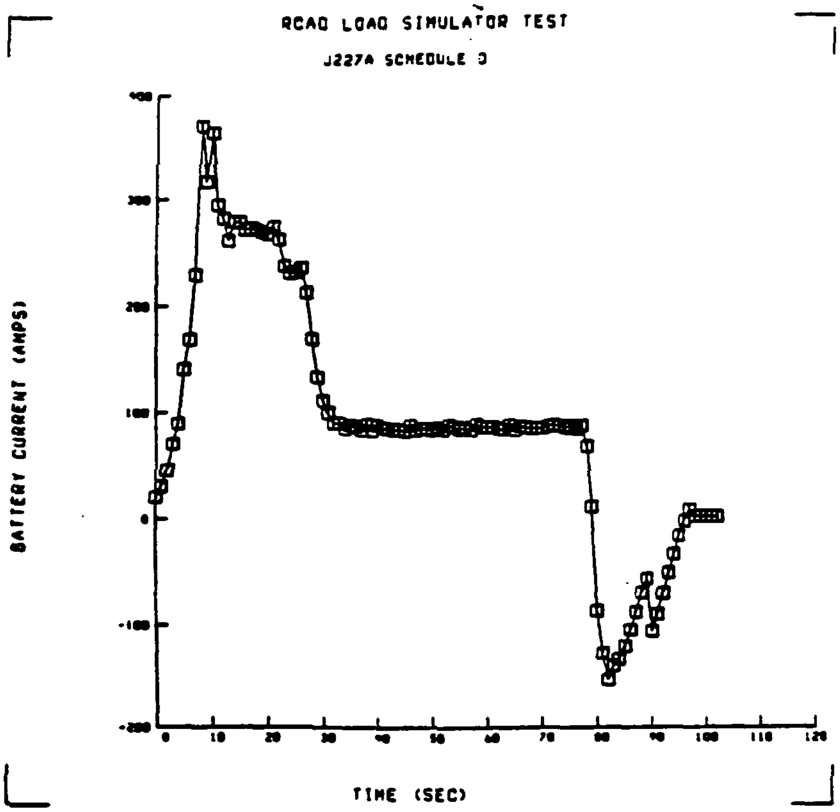


Figure 4-3. Comparison of HEAVY and RLS Results - Vehicle Velocity

MEASURED RESULTS



SIMULATED RESULTS

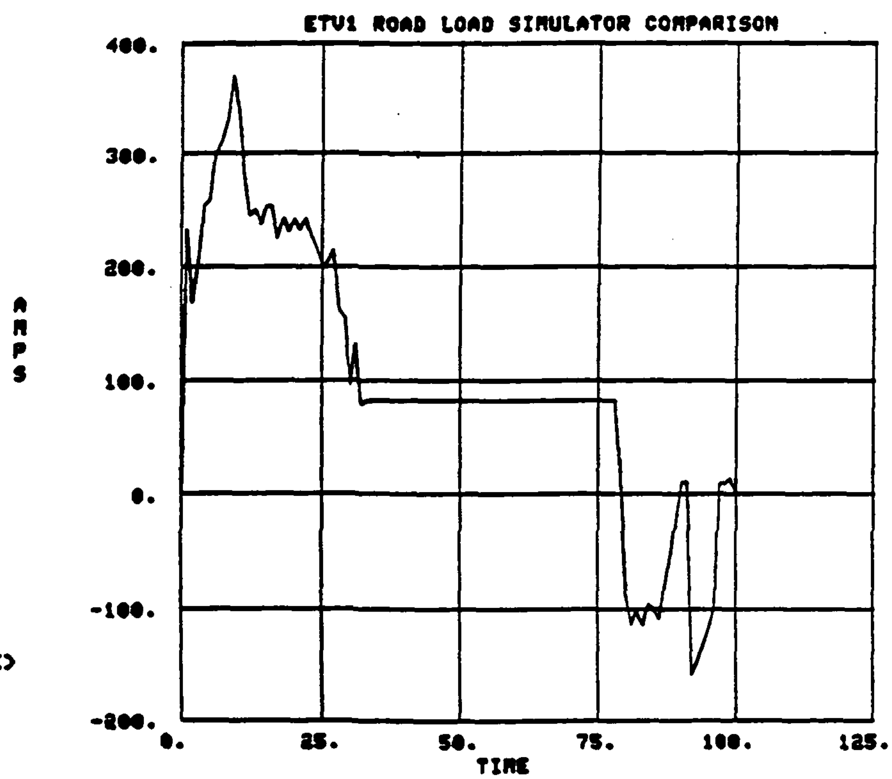
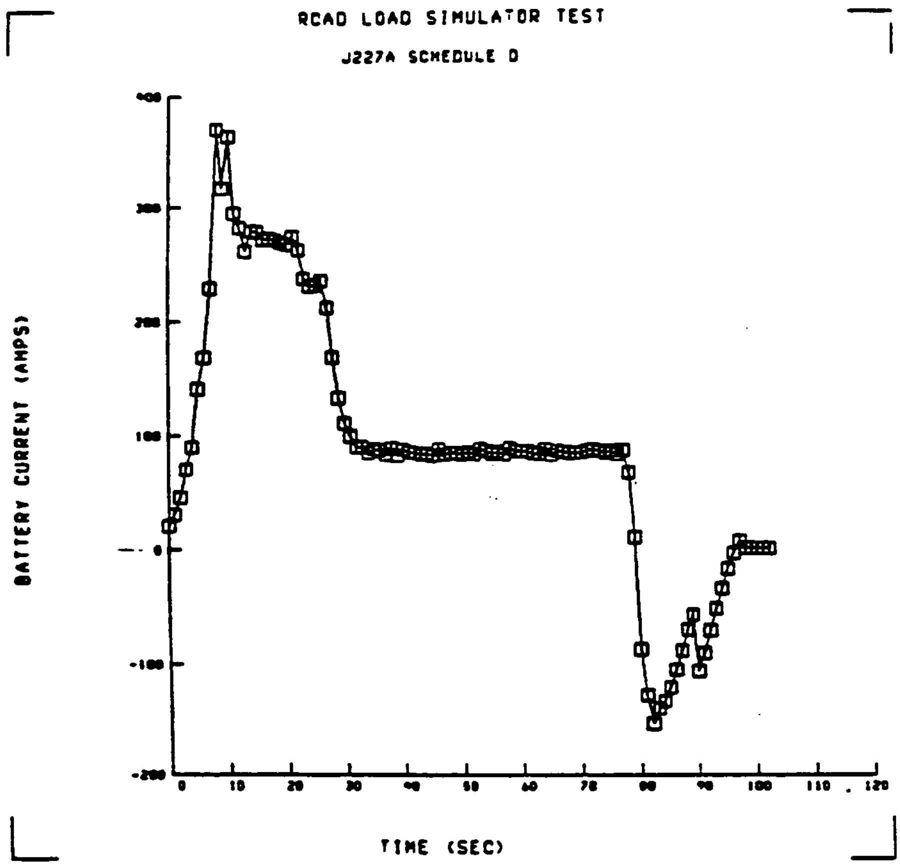


Figure 4-4. Comparison of HEAVY and RLS Results - Battery Current

MEASURED RESULTS



SIMULATED RESULTS

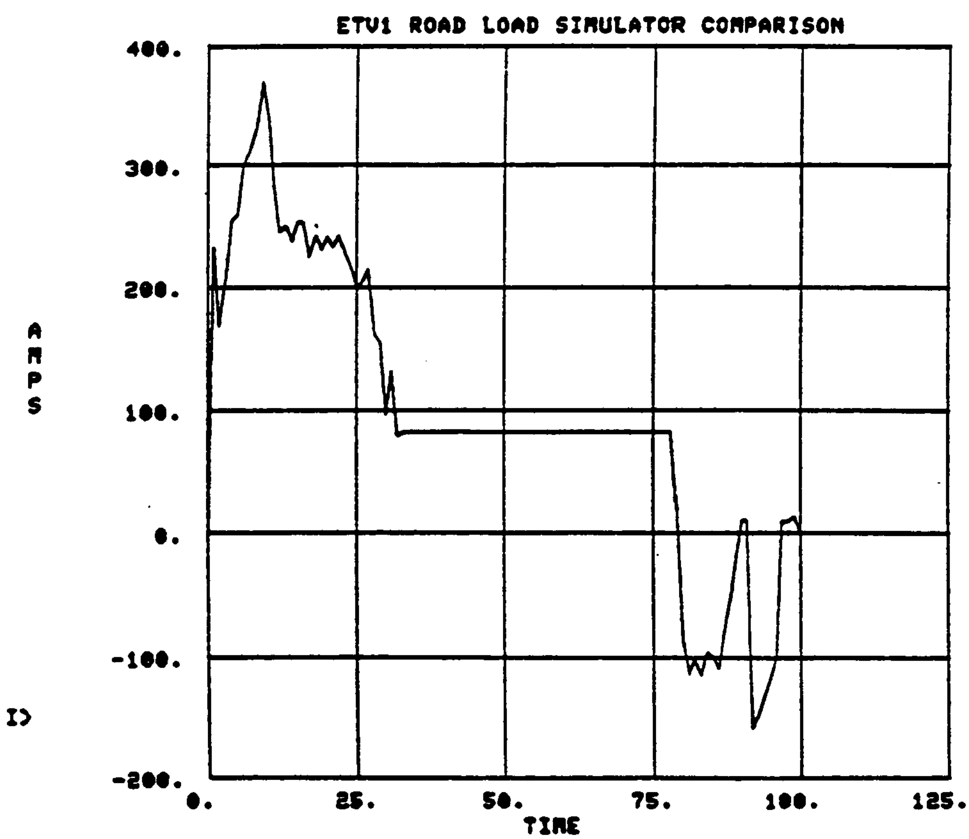


Figure 4-5. Comparison of HEAVY and RLS Results - Battery Power

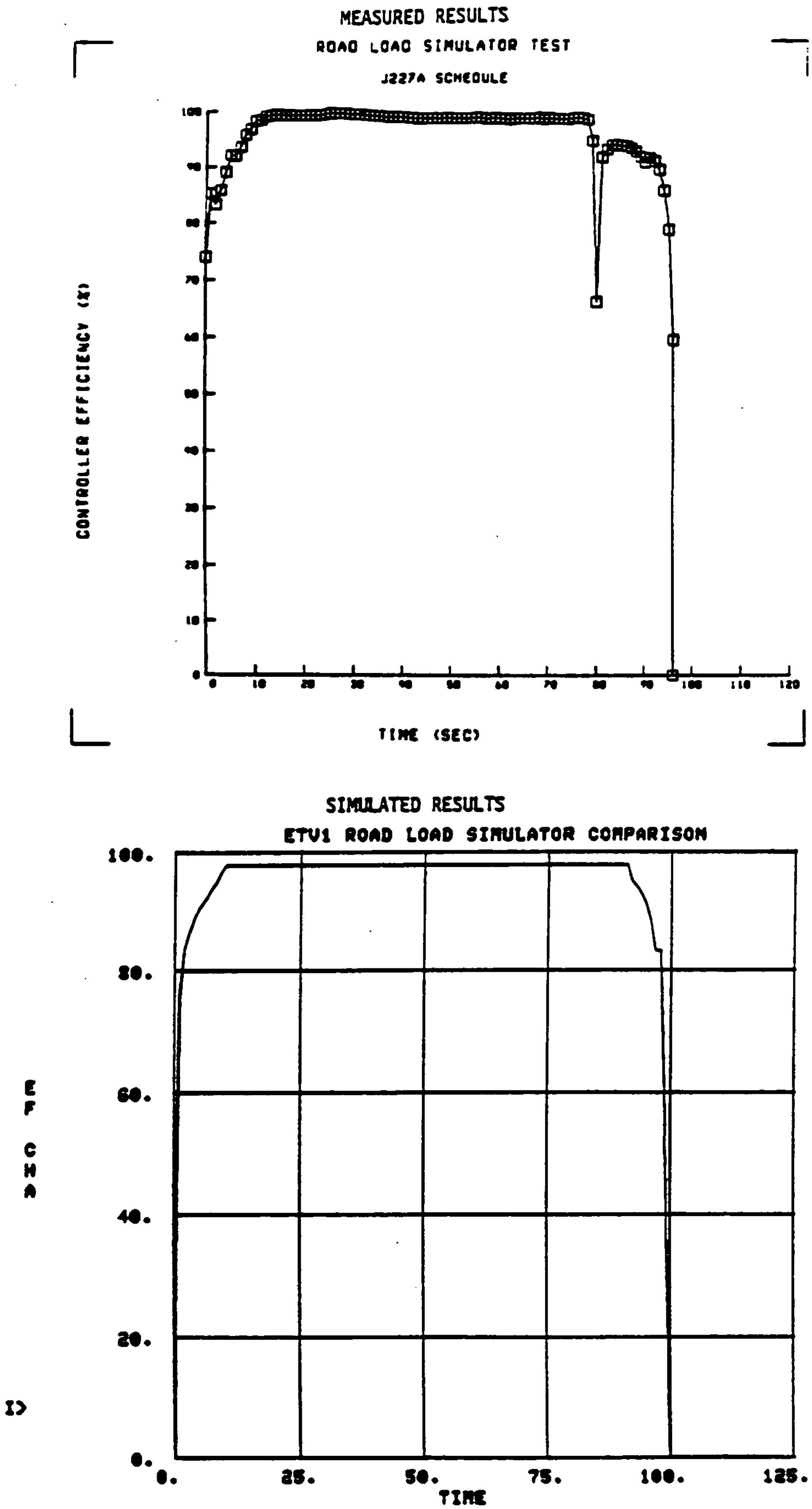
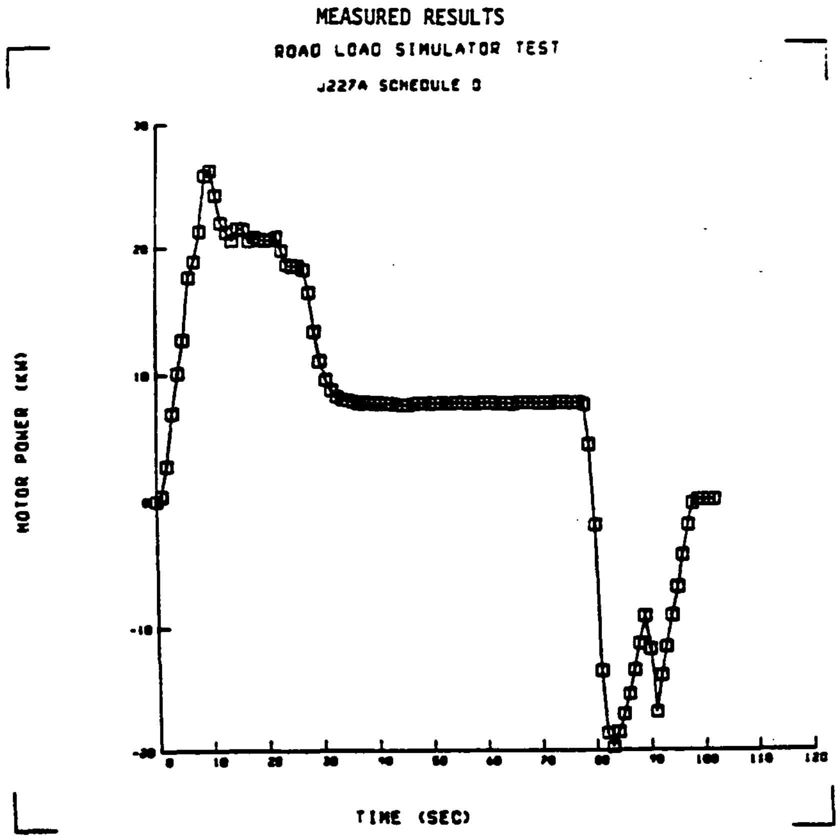


Figure 4-6. Comparison of HEAVY and RLS Results - Controller Efficiency



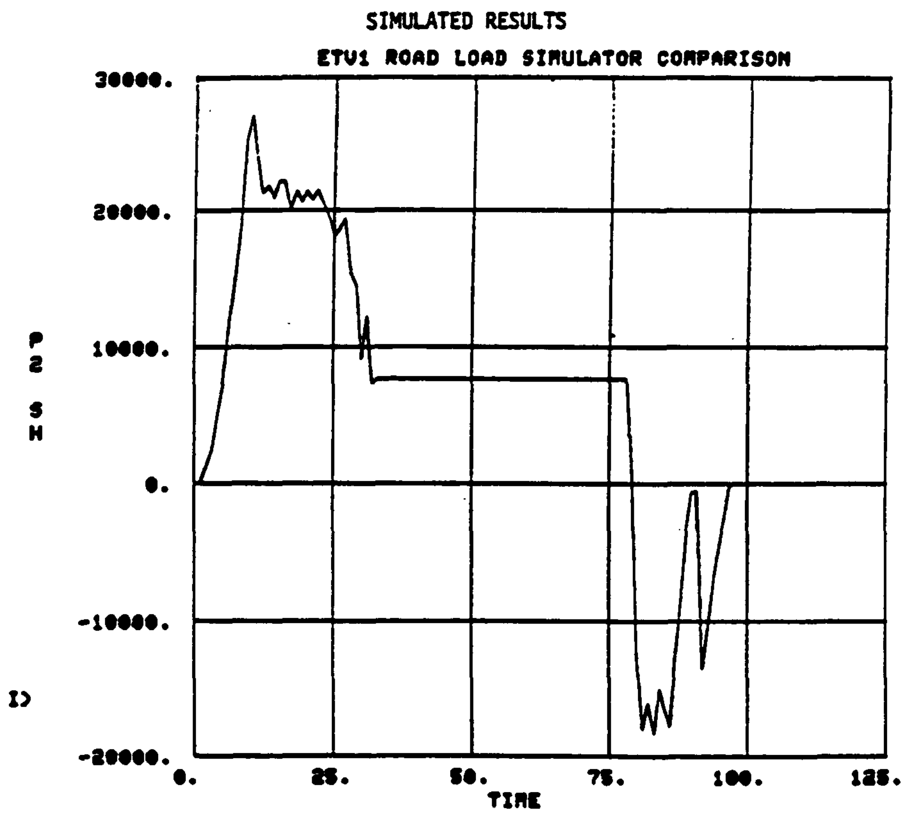
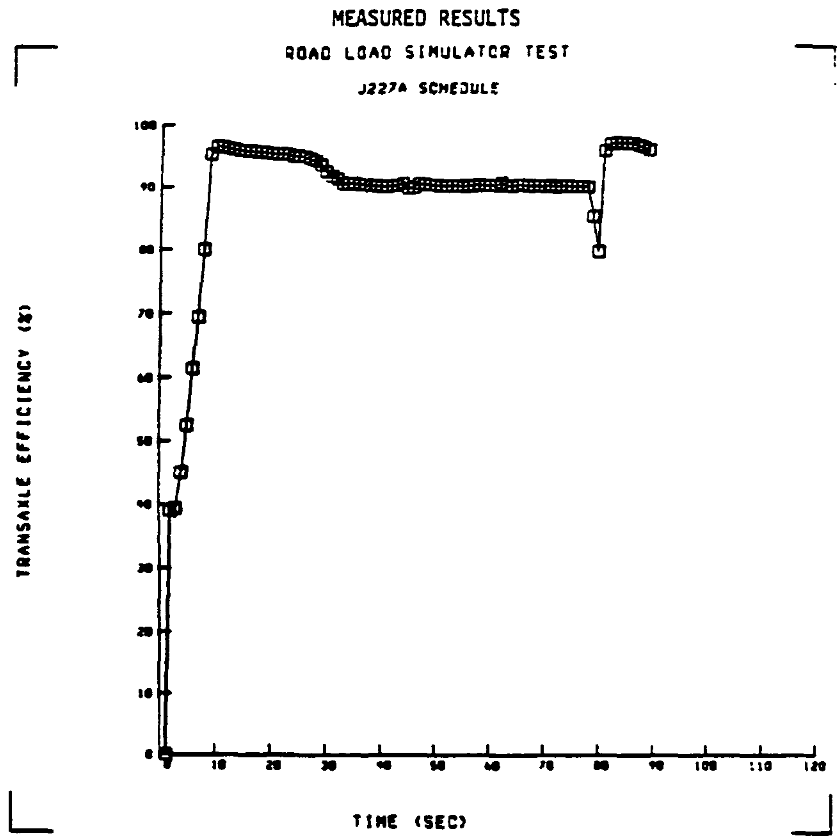


Figure 4-7. Comparison of HEAVY and RLS Results - Motor Power



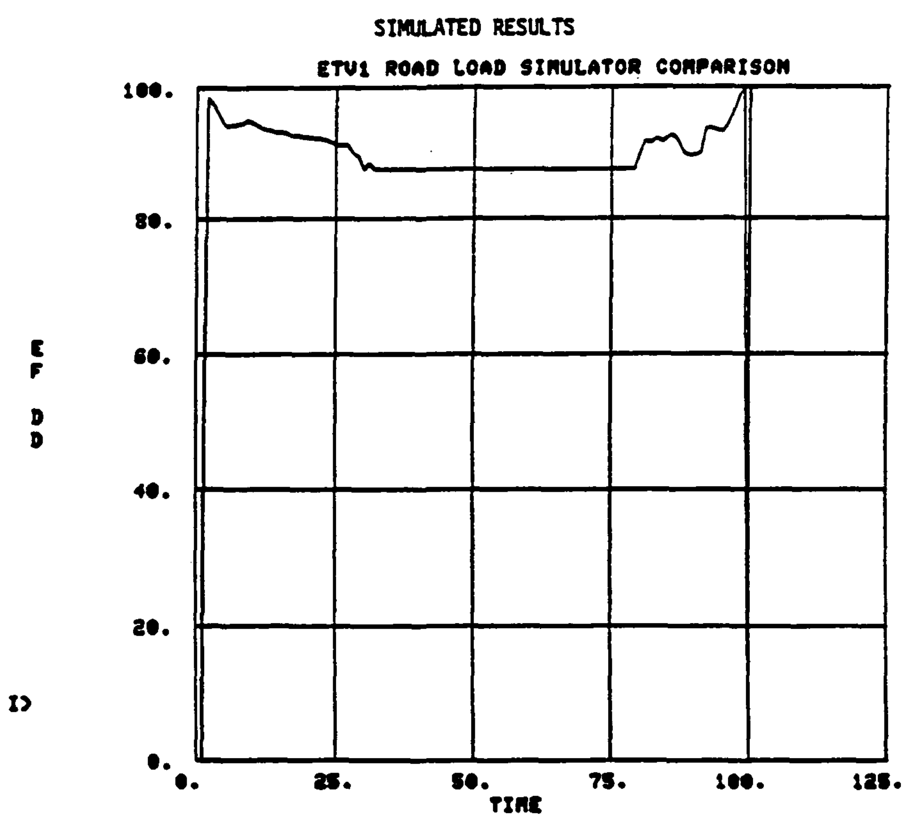


Figure 4-8. Comparison of HEAVY and RLS Results - Transaxle Efficiency

5.0 EXAMPLE 3 - PARALLEL HYBRID VEHICLE

This example was chosen to show how HEAVY can be used to model a hybrid vehicle and investigate performance variations caused by changes to the energy management strategy.

5.1 VEHICLE AND MISSION DESCRIPTION

The baseline drive train for this study is described in reference 3. Conceived as a front-wheel drive unit for a five-passenger automobile, it is a parallel hybrid drive train using a heat engine and an advanced electrically commutated machine as prime movers. The baseline energy management strategy blends power from the two prime movers to yield acceptable performance, range and energy economy.

Figure 5-1 is a block diagram of the drive train showing its configuration and key parameters. The gearbox downstream from the electric machine helps to match the desirable operating speed of the electric machine to that of the heat engine. The continuously variable transmission is controlled to place the electric machine near its optimum operating speed. The range of transmission ratios, 0.3:1 (overdrive) to 3:1 allows excellent motor speed control over most of the operating envelope of the vehicle. The step-down gear and chain drive downstream from the continuously variable transmission match its output speed to that of the driven wheels.

Reference 3 discusses the baseline energy management strategy in some detail and includes consideration of effects such as hill climbing, cold versus hot starting, mechanical wear, sludge buildup, and crankcase ventilation. For the purposes of this study, only the three basic modes of the energy management strategy need be considered:

- Low speed — At speeds below a velocity threshold (baseline 3 km/h) the heat engine is arbitrarily declutched to prevent stalling.
- Electric — As long as battery state of charge is above a threshold (baseline 20%) then energy is managed as shown in Table 5-1.

- Heat engine — When battery state of charge falls below the threshold, energy is managed as shown in Table 5-2.

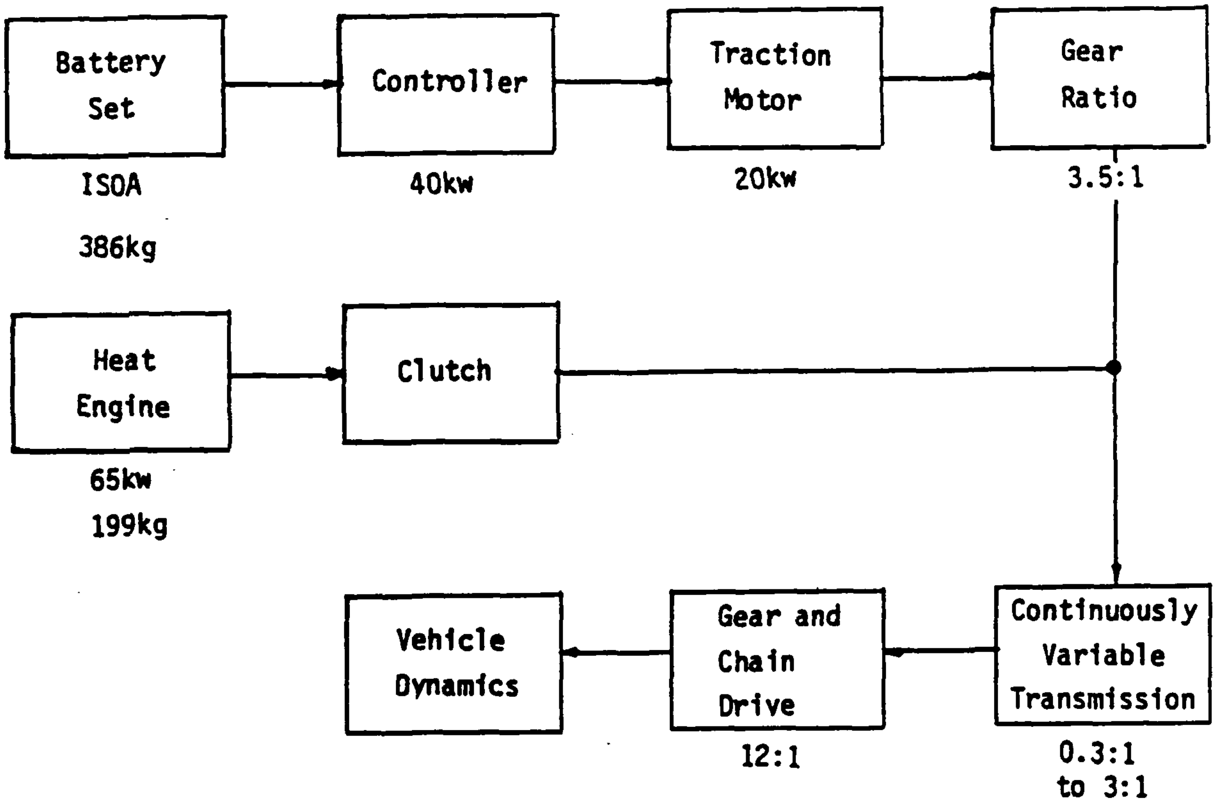


Figure 5-1. Block Diagram of Example Hybrid Drive Train

Table 5-1

ENERGY MANAGEMENT STRATEGY
IN ELECTRIC MODE

Vehicle State	Percent of Power Demand Supplied or Accepted: Battery	Heat Engine
cruise	100%	0%
acceleration	30%	70%
braking	100%	0%

Table 5-2

ENERGY MANAGEMENT STRATEGY
IN HEAT ENGINE MODE

Vehicle State	Percent of Power Demand Supplied or Accepted: Battery	Heat Engine
cruise	0%	100%
acceleration	30%	70%
braking	100%	0%

Reference 1 contains a daily range frequency schedule which describes nine trips making up the missions for the baseline vehicle. This schedule, implemented in the HEAVY life cycle cost component, is shown in Table 5-3. Daily trips shorter than 80 km are assumed to be made up of SAE J227a, schedule D cycles. Longer trips are made up of 16 D-cycles equally divided between the beginning and the end of the trip and the remainder of cruise at 90 km/h.

Table 5-3

YEARLY TRIP SCHEDULE FOR EXAMPLE HYBRID VEHICLE

Daily Range km	No. of Days Per Year	Total Range Per Year - km
0	16	0
10	130	1300
30	85	2550
50	57	2850
80	54	4320
130	12	1560
160	7	1120
500	3	1500
800	1	800
Totals	365	16000

5.2 MODEL GENERATION

Figure 5-2 is a block diagram of the baseline vehicle and drive train rearranged into a format compatible with HEAVY model generation. Each block in Figure 5-1 has a corresponding block on this diagram. The names of the HEAVY standard components corresponding to each system element are in the lower left corner of each block. As usual, several blocks required for HEAVY model generation were added:

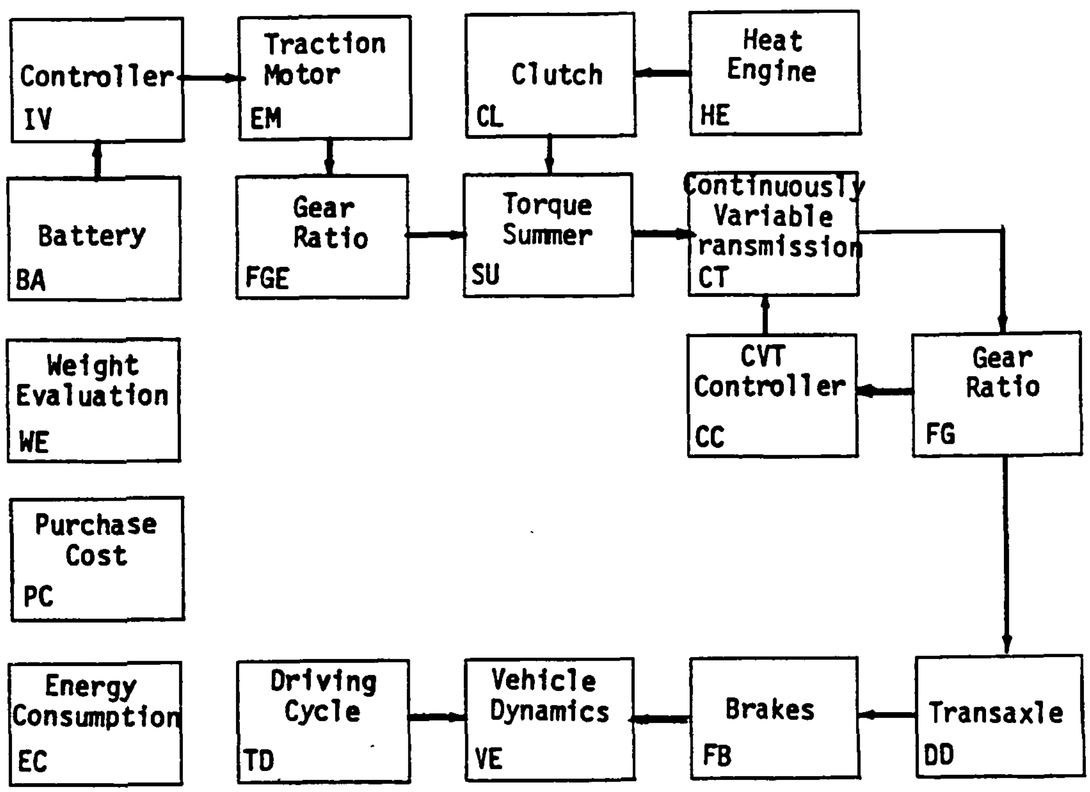


Figure 5-2. HEAVY Schematic of Example Hybrid Vehicle

Torque Summation — The point at which the clutch and the gearbox drive a common shaft is represented by a SUmmer component from the HEAVY library. The SU component contains built-in logic to implement power request priority and split.

CVT Control — The CVT Controller (CC) component adjusts CVT ratio within specified limits to keep the input-shaft speed at a specified value.

Driving Cycle — The TD component provides the vehicle with velocity commands representing each of the four schedules in the SAE J227a specification.

Several other blocks were added to request summary output from each simulation case run:

Weight Evaluation — The WE component prints a weight statement for the vehicle.

Purchase Cost — The PC component calculates and prints a purchase cost summary for the vehicle.

Energy Consumption — The EC component summarizes the fossil fuel and electricity used in each simulation run made with the model.

Figure 5-3 is a logic diagram implementing the baseline energy management strategy as described above. This logic was represented using logic blocks from the HEAVY component library. The logical compare blocks monitor state of charge, vehicle velocity and velocity command; comparing these items to stated thresholds. The logical AND and OR blocks implement the logic expressions to determine operating mode. Power split during acceleration is managed through the SUmmer component.

The schematics of Figures 5-2 and 5-3 were translated into HEAVY model generation commands, one command for each block on the schematics. Table 5-4 shows the HEAVY model generation commands to implement the baseline system model.

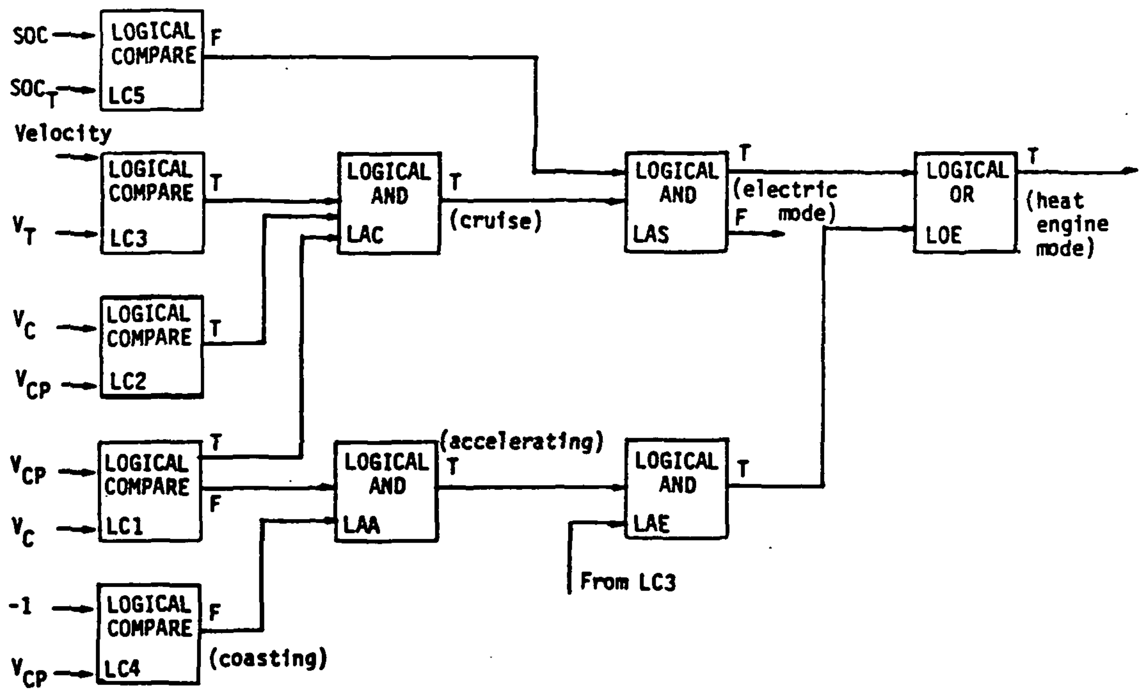


Figure 5-3. HEAVY Schematic of Energy Management Logic for Example Hybrid Vehicle

Table 5-4

MODEL GENERATION COMMANDS FOR EXAMPLE HYBRID DRIVE TRAIN

```
MODEL DESCRIPTION=GARRETT/AIRESEARCH HYBRID-ELECTRIC VEHICLE
LOCATION=21      BA
LOCATION=01      IV      INPUTS=BA
LOCATION=03      EM      INPUTS=IV
LOCATION=23      FGE     INPUTS=EM
LOCATION=07      HE
LOCATION=05      CL      INPUTS=HE,LOE(TRU=E)
LOCATION=25      SU      INPUTS=FGE,CL,LAS(FAL=PR,1),LOE(TRU=PR,3)
LOCATION=110     LOE     INPUTS=LAE(TRU=L1),LAS(TRU=L2)
LOCATION=130     LAE     INPUTS=LAA(TRU=L1),LC3(TRU=L2)
LOCATION=108     LAS     INPUTS=LAC(TRU=L1),LC5(FAL=L2)
LOCATION=144     LAA     INPUTS=LC1(FAL=L1),LC4(FAL=L2)
LOCATION=148     LAC     INPUTS=LC1(TRU=L1),LC2(TRU=L2),LC3(TRU=L3)
LOCATION=106     LC5     INPUTS=BA(ST,2=L1)
LOCATION=142     LC4     INPUTS=TD(VCS=L2)
LOCATION=150     LC3     INPUTS=VE(VV,1=L1)
LOCATION=168     LC2     INPUTS=TD(VC,2=L1,VCS=L2)
LOCATION=146     LC1     INPUTS=TD(VCS=L1,VC,2=L2)
LOCATION=27      CT      INPUTS=SU,CC(RC=RC)
LOCATION=47      CC      INPUTS=FG(W,1=W,2)
LOCATION=49      FG      INPUTS=CT
LOCATION=69      DD      INPUTS=FG
LOCATION=67      FB      INPUTS=DD
LOCATION=65      VE      INPUTS=FB,TD
LOCATION=63      TD
LOCATION=41      WE
LOCATION=51      PC
LOCATION=61      EC
END OF MODEL
PRINT
```

5.3 SIMULATION

Table 5-5 shows the HEAVY analysis commands to set parameter values and perform a single SAE J227a, schedule D driving cycle. Similar commands were used to perform the various runs described in the next section.

Table 5-5

ANALYSIS COMMANDS FOR EXAMPLE HYBRID DRIVE TRAIN

```
TITLE=GARRETT/AIRESEARCH HYBRID
PARAMETER VALUES
     L2 LC3=0.833, L1 LC4=-1., L2 LC5=0.5
     WO HE=110.
     WF1SU=.3, WF3SU=.7
     S  IV=1.
     WI CL=0., WI HE=199., WI EM=12., WI IV=36., WI DD=59.
     WC BA=4.6
     R  FGE=3.5, R  FG=12., D  DD=1.
     WC CC=300., RL CC=0.3, RH CC=3.
     S  HE=4., TX HE=154.3
     S  TD=4.
     PR4SU=0., PR5SU=0.
     JI HE=.03, JI FGE=0., JI CT=0., JI FG=0., JI DD=0., JI FB=0.
     CA BA=393.2, NC BA=84.
     RT EM=13.6
     RP CT=90000., RT CT=215.
     WI FG=0.
     RP DD=90000., RT DD=774.
PRINTER PLOTS
PRINT CONTROL=3., TINC=.5, TMAX=122.
OUTRATE=1.    PRATE=1.
DISPLAY1
     VV1VE,VS,TIME
DISPLAY2
     T2 CL,VS,TIME
     T2 FGE,VS,TIME
SIMULATE
```

5.4 RESULTS

5.4.1 Baseline System Performance

Figure 5-4 is a plot of vehicle velocity over an SAE J227a, schedule D driving cycle with fresh batteries. Vehicle performance comes very close to command as expected.

The baseline energy management strategy calls for cruise power to be taken from the battery until 20% state of charge is reached. Vehicle performance is somewhat degraded and battery life is seriously reduced if the batteries are discharged below 20% state of charge. Therefore the threshold for switch

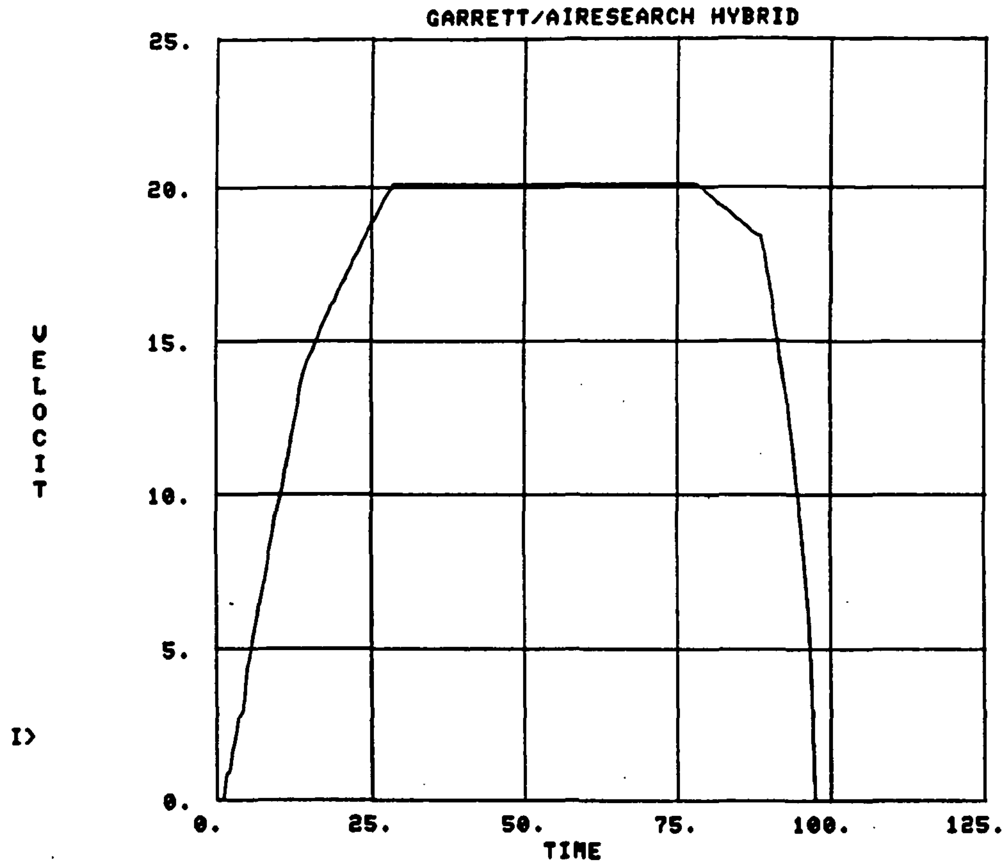


Figure 5-4. D-Cycle Velocity Profile for Example Hybrid Vehicle

from electric to heat engine mode should be somewhat higher than 20%—high enough that all the daily trip missions may be completed without falling below 20% state of charge. Estimates from the simulation of the D-cycle show that if the threshold is set at 25% state of charge, then all daily trips will be completed without falling below 20% state of charge. This threshold was used for the remaining runs made.

Figure 5-5 shows the yearly trip performance for the baseline system. This table, generated by the HEAVY life cycle cost model, shows that the yearly distance traveled is 16000 km. The trip schedule uses 2574 kWh of electricity and 310 kg of fossil fuel. These trips result in the equivalent of 152 battery cycles (20% state of charge).

YEARLY TRIP PERFORMANCE

TRIP	TOTAL DISTANCE (KM)	ENERGY/ TRIP (KWH)	TOTAL ENERGY (KWH)	FOSSIL FUEL/TRIP (KG)	TOTAL FOSSIL FUEL (KG)	BATTERY CYCLES/ TRIP	TOTAL BATTERY CYCLES
1	1300.	1.878	244.1	.1681	21.86	.2398	31.17
2	2550.	5.633	478.8	.5044	42.88	.3118	26.51
3	2850.	9.388	535.1	.8407	47.92	.4056	23.12
4	4320.	17.09	922.8	.7740	41.80	.9278	50.10
5	1560.	17.09	205.1	2.966	35.59	.9278	11.13
6	1120.	17.09	119.6	4.281	29.97	.9278	6.495
7	1500.	17.09	51.27	19.19	57.56	.9278	2.784
8	800.0	17.09	17.09	32.34	32.34	.9278	.9278
TOTALS	.1600E+05		2574.		309.9		152.2

Figure 5-5. Yearly Trip Performance for Example Hybrid Vehicle

The life cycle cost model assumes that the battery set will sustain 500 cycles, so the battery set need not be replaced until the seventh year of the vehicle's 10-year life.

Figure 5-6 is the final output of the life cycle cost model. It gives a breakdown of purchase cost, direct operating cost, maintenance and repair cost and salvage value. Life cycle cost is then reported in total, per km driven and per year. While costs are reported in dollars, please recognize that the most important use of a cost model is in predicting trends, not absolute numbers. To emphasize this fact, the results that follow do not show dollars on the payoff axis of the figures.

5.4.2 Effect of Power Split on Direct Operating Cost

The baseline energy management strategy requests 30% electric and 70% heat engine power during acceleration. Variations in the power split during

OPERATING COST MODEL

LIFE CYCLE COST
160000.00 KM OVER 10 YEARS

	$'S	$/KM	$/YR
PURCHASE COST	11940.06	.075	1194.01
DIRECT OPERATING COSTS			
FOSSIL FUEL	1704.47	.011	170.45
ELECTRICITY	1286.90	.008	128.69
MAINTENANCE & REPAIR COSTS			
BATTERY: MAINTENANCE	338.80	.002	33.88
REPLACEMENT	1156.11	.007	115.61
PROPULSION SYSTEM	+ 3883.87	+ .024	+ 388.39
TOTAL COST	20310.21	.127	2031.02
SALVAGE VALUES			
VEHICLE	- 1194.01		
BATTERY	- 44.44		
LIFE CYCLE COST	19071.77	.119	1907.18

Figure 5-6 Life Cycle Cost Summary for Example Hybrid Vehicle

acceleration have a strong influence on direct operating cost — cost of electricity used and cost of fossil fuel used. A HEAVY run was made in which the percent of electric power requested was varied from 20% to 100%. With the default cost factors used in HEAVY, 0.05 $/kWh and 1.55 $/kg, the results show that direct operating cost goes down as the percentage of electric power goes up. If the cost of amortizing battery replacement is included, then the slope is less but the conclusion remains the same. The top line on Figure 5-7 shows this data with default cost factors.

However, direct operating cost is very sensitive to heat engine performance. The heat engine model used for this run, typical of today's technology, delivers about 23 km/kg (40 mpg) at cruise. The other lines on Figure 9 represent the use of more efficient heat engines — the engine represented on the third line delivers about 46 km/kg (80 mpg). If the expected improvements in heat engine technology are realized then the power split during acceleration may have an optimum value.

Cruise: 100% electric

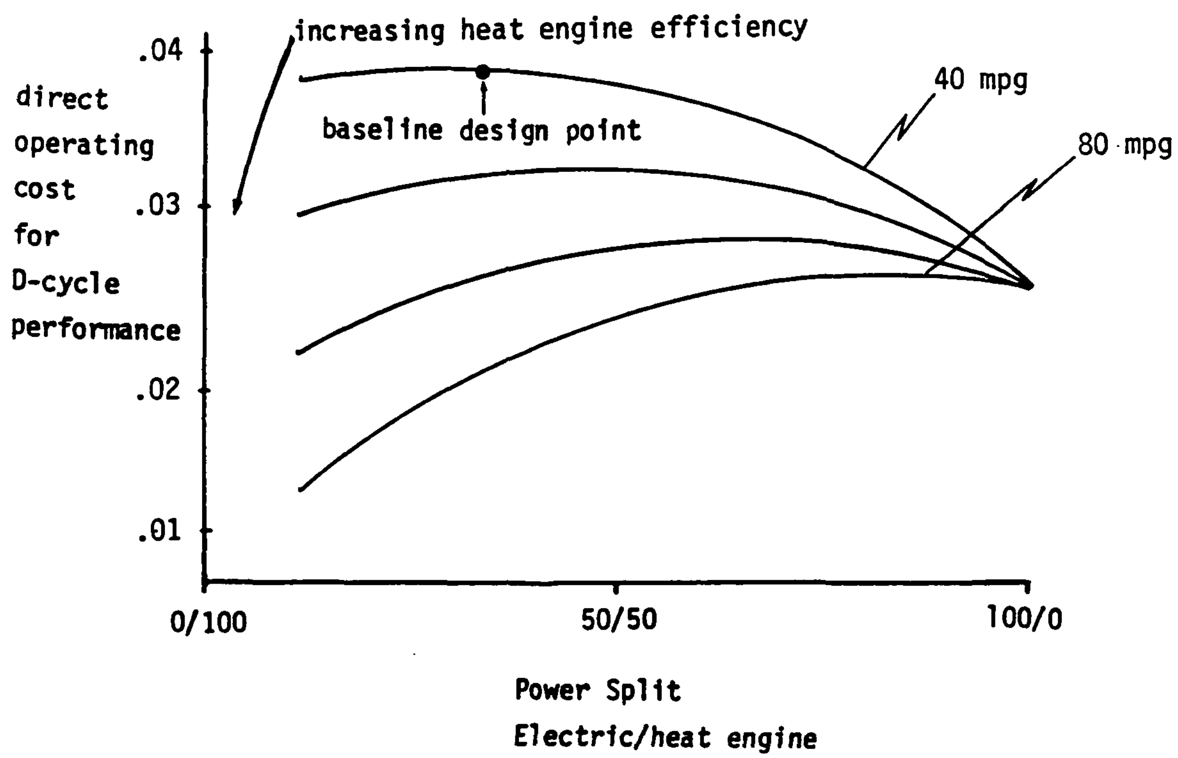


Figure 5-7 Effect of Power Split During Acceleration on Direct Operating Cost

5.4.3 Effect of Cruise Strategy on Direct Operating Cost

The energy management strategy was modified to always use the heat engine for cruise but maintain the 30/70 power split during acceleration. A HEAVY run was made in which the velocity threshold for engaging the heat engine was set to progressively higher values. This strategy simulates a hybrid that performs all low-speed driving with the electric and uses the heat engine for sustained cruise and acceleration.

The top line on Figure 5-8 shows direct operating cost for D-cycles using the default cost factors for electricity and fossil fuel. Again, the conclusion is to use the electric drive as much as possible to reduce direct operating cost. As in the previous case, this conclusion is very sensitive to heat engine performance as the lower lines on Figure 5-8 show.

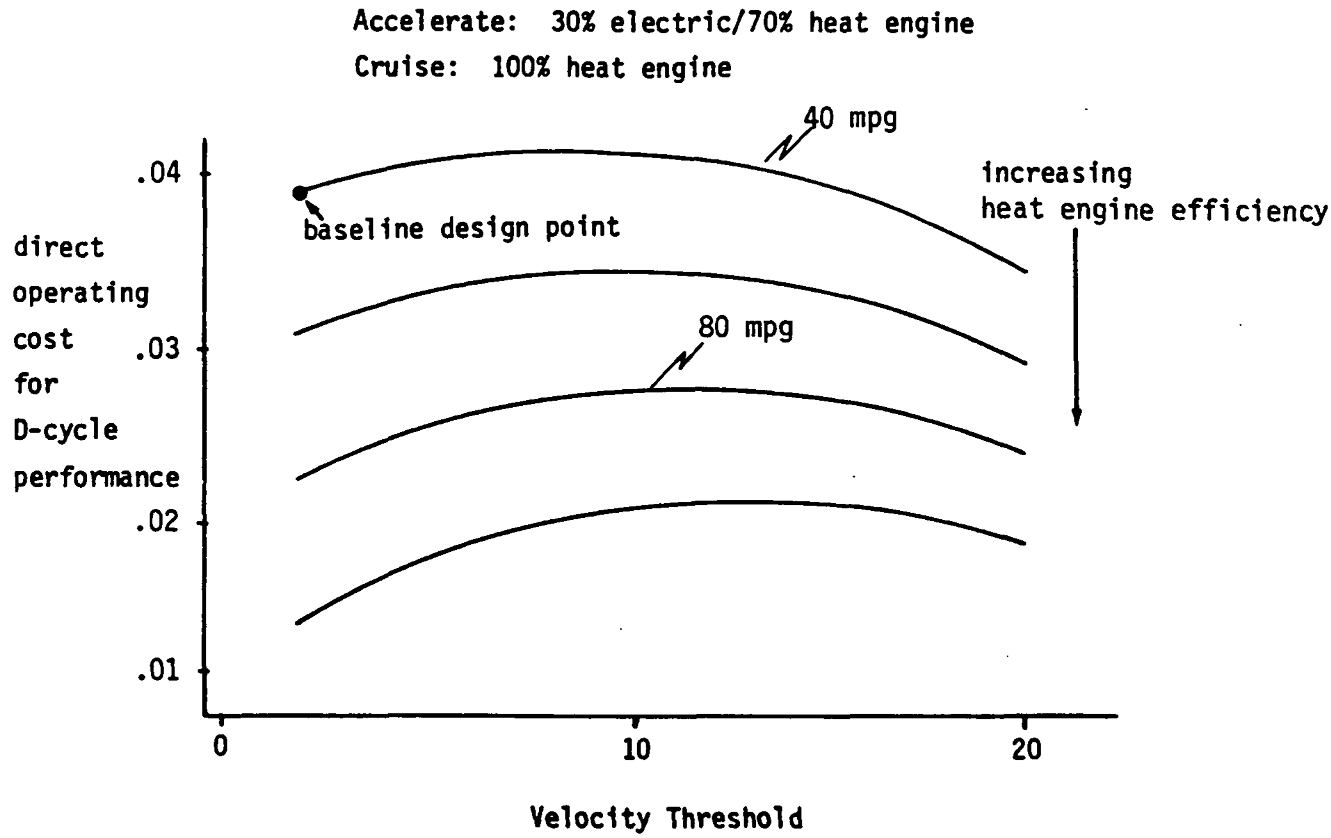


Figure 5-8. Effect of Heat Engine Engage Velocity on Direct Operating Cost

5.4.4 Effect of Battery Capacity on Life Cycle Cost

Figure 5-5, the yearly trip summary, shows that a 50 km trip does not nearly deplete the battery set. The equivalent cycle value of 0.4056 means that the final state of charge was 66%. For this, the longest trip composed entirely of D-cycles, the heat engine is never used for cruise and the vehicle completes the trip with excess capacity.

A HEAVY run was made in which the battery weight (and therefore capacity) was reduced until the final state of charge was just above the 20% threshold. Figure 5-9 summarizes the data obtained from this run.

As battery capacity is reduced, the life cycle cost drops because of decreased battery cost and improved energy economy due to decreased vehicle weight. Battery cycles per year increases and final state of charge for the 50 km trip decreases reflecting the lowered battery capacity. Cost continues

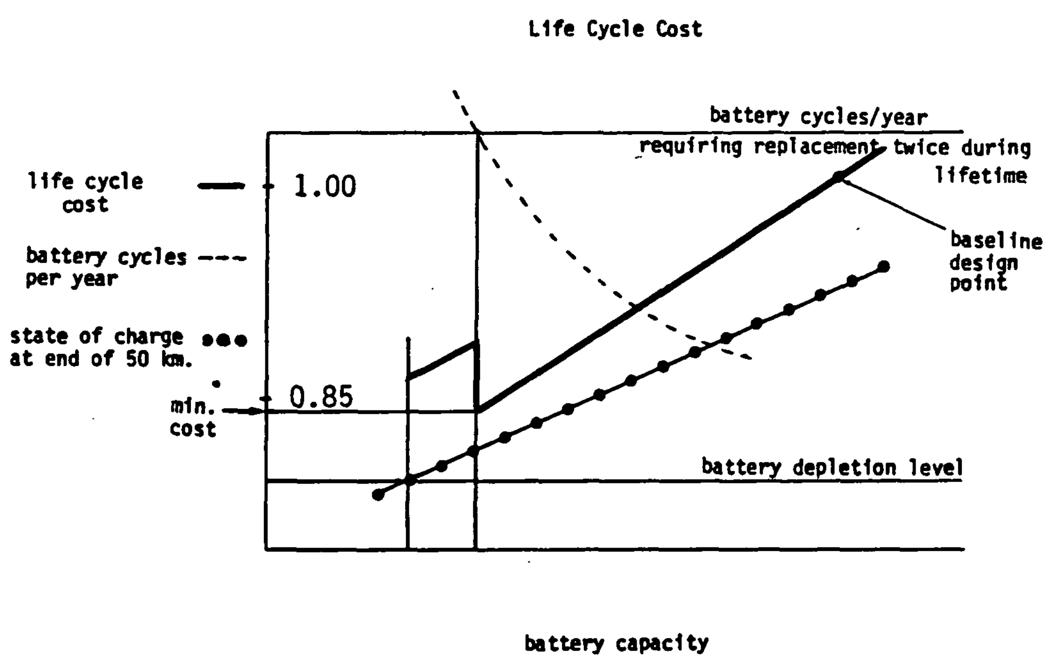


Figure 5-9. Effect of Battery Capacity on Life Cycle Cost

to decrease until the number of battery cycles reaches the number which requires battery replacement twice during the vehicle's 10-year life. At this point the cost jumps reflecting the cost of the extra battery replacement. Cost then continues to decrease until the battery capacity is no longer sufficient to complete the 50 km trip without dropping below 20% state of charge.

Minimum life cycle cost occurs at the battery capacity just above the value which requires an additional battery replacement during the vehicle lifetime. Choosing this capacity would result in the second battery set installed completing its cycle life at the time the vehicle is to be scrapped.

The analysis described here shows that direct operating cost and life cycle cost are both sensitive to the logic and parameters of the energy management strategy. The effects observed would have been difficult to predict with hand analysis. The components of the HEAVY library allow the designer to quickly and easily define a proposed hybrid vehicle and implement its energy

management strategy. The HEAVY simulation program allows the designer to economically perform trade-off and sensitivity studies to support his design activities.

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6.0 EXAMPLE DRIVE TRAIN CONFIGURATIONS

This section contains descriptions of 10 drive trains that have been simulated with HEAVY. Each description includes:

- A brief written description of the drive train
- The HEAVY model generation statements which define the model
- A set of HEAVY simulation commands to exercise the model

All of these drive trains have been tested over an SAE J227a, schedule D, driving cycle and all performed in a physically reasonable way.

These models are presented for three reasons:

- To illustrate the variety of drive trains that may be modeled with HEAVY
- To provide further examples of HEAVY model generation commands
- To provide a starting point for users who wish to model similar drive trains

Please regard these models as representative of generic drive trains and not necessarily faithful models of a specific vehicle. The performance of those models identified as representative of a specific vehicle has been compared with other available data and found to agree to a reasonable level.

6.1 D.C. Series Machine Drive Train

This configuration is used as an example in Section 3 of this document. It represents the simplest electric drive train as used in golf carts and electric factory trucks.

Table 6-1

MODEL GENERATION COMMANDS FOR THE D.C. SERIES MACHINE DRIVE TRAIN

```
MODEL DESCRIPTION = SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE
LOCATION = 21, BA
LOCATION = 23, CH      INPUTS = BA
LOCATION = 25, SE      INPUTS = CH
LOCATION = 27, DD      INPUTS = SE
LOCATION = 47, FB      INPUTS = DD
LOCATION = 67, VE      INPUTS = FB, TD
LOCATION = 65, TD
LOCATION = 01, EC
LOCATION = 03, PC
LOCATION = 05, WE
END OF MODEL
PRINT
```

Table 6-2

ANALYSIS COMMANDS FOR THE D.C. SERIES MACHINE DRIVE TRAIN

```
TITLE = SERIES FIELD MACHINE DRIVE TRAIN EXAMPLE
PARAMETER VALUES  S  TD = 4
TMAX = 122.
TINC = 0.5
PRINTER PLOTS
PRINT CONTROL = 3
DISPLAY1
  VV1VE, VS, TIME
DISPLAY2
  I1 CH, VS, TIME
  T2 SE, VS, TIME
DISPLAY3
  EF CH, VS, TIME
  EF SE, VS, TIME
  EF DD, VS, TIME
SIMULATE
```

6.2 Heat Engine Drive Train

This model represents a subcompact heat engine drive train. It is the simplest configuration for which a clutch is required.

Table 6-3

MODEL GENERATION COMMANDS FOR THE HEAT ENGINE DRIVE TRAIN

```
MODEL DESCRIPTION=HEAT ENGINE ALONE
LOCATION=12,HE
FORTRAN STATEMENTS
      E  CL=0.
      IF (TIME.GT.1.) E  CL=1.
LOCATION=14,CL,INPUTS=HE
LOCATION=16,FT,INPUTS=CL
LOCATION=18,DD,INPUTS=FT
LOCATION=20,FB,INPUTS=DD
LOCATION=40,VE,INPUTS=FB,TD
LOCATION=38,TD
END OF MODEL
PRINT
```

Table 6-4

ANALYSIS COMMANDS FOR THE HEAT ENGINE DRIVE TRAIN

```
TITLE=HEAT ENGINE ALONE
INITIAL CONDITIONS=VV1VE=0.
PARAMETER VALUES
WO HE=150.
JI HE=.068,TX HE=174.9,S  TD=0.
WX HE=460.8,S  HE=3.
E  CL=0.
D  DD=2.84,A  VE=1.982
RW VE=.32
TINC=.25
TMAX=122.
PRINT CONTROL=3.
PRINTER PLOTS
DISPLAY1,PV1VE,VS,TIME
VV1VE,VS,TIME
T2 HE,VS,TIME
GN FT,VS,TIME
SIMULATE
```

6.3 Induction Machine Drive Train

This model represents the Eaton a.c. drive train. The Eaton vehicle uses a two-speed transaxle rather than the four-speed manual transmission used in this model.

Table 6-5

MODEL GENERATION COMMANDS FOR THE INDUCTION MACHINE DRIVE TRAIN

```
MODEL DESCRIPTION=EATON A.C. VEHICLE
LOCATION=021   BA
LOCATION=023   IV   INPUTS=BA
LOCATION=025   IM   INPUTS=IV
LOCATION=027   FT   INPUTS=IM
LOCATION=045   FB   INPUTS=FT
LOCATION=065   VE   INPUTS=FB,GR,TD
LOCATION=067   GR
LOCATION=063   TD
LOCATION=069   WE
LOCATION=070   EC
END OF MODEL
PRINT
```

Table 6-6

ANALYSIS COMMANDS FOR THE INDUCTION MACHINE DRIVE TRAIN

```
TITLE=EATON A.C. VEHICLE ANALYSIS DATA
PARAMETER VALUES
S  TD=4.
NC BA=72., WI IV=50., WI IM=57.5, JI IM=.0129, WI FT=39., RT FT=95.
JI FT=.002202, R1 FT=19.8, RS FT=8.23, RW VE=.2667, A  VE=2.551
WF VE=617., PM VE=0., K  VE=0.
TABLE   GT FT(4,2)
0., 100000.
0., 47.6, 1000., 2000.
1., 2., 3., 4.
1., 2., 3., 4.
TABLE   GC FT(4,2)
0., 100000.
0., 38.17, 1000., 2000.
1., 2., 3., 4.
1., 2., 3., 4.
PRINTER PLOTS
    PRINT CONTROL=3     TMAX=100.     TINC=.1
OUTRATE=10.
DISPLAY1,VV1VE,VS,TIME
         T2 IM,VS,TIME
          V2 IV,VS,TIME
         F2 IV,VS,TIME
         I1 IV,VS,TIME
DISPLAY2,V2 BA,VS,TIME
         GN FT,VS,TIME
         SL1IM,VS,TIME
         VH1IM,VS,TIME
SIMULATE
```

6.4 D.C. Shunt Machine Drive Train

This model is a simplified representation of the GE/Chrysler ETV1 vehicle. The armature circuit chopper and the field circuit chopper are connected to the battery set through a current accumulator which represents the point at which the two parallel paths separate. The simplification is in the control electronics. In this model the default logic in the HEAVY standard components is used to control the shunt field machine. The machine automatically switches from armature to field control mode at base speed and the armature chopper remains in the circuit even when its duty cycle is unity.

Notice that all connections are made by mentioning the upstream component names, but that port assignments are given for the two choppers. Port assignments are necessary only for components with multiple downstream ports such as the current accumulator.

Table 6-7

MODEL GENERATION COMMANDS FOR THE D.C. SHUNT MACHINE DRIVE TRAIN

```
MODEL DESCRIPTION=D.C. SHUNT MACHINE
LOCATION=021   BA
LOCATION=023   CA   INPUTS=BA
LOCATION=007   CHA   INPUTS=CA(2=1)
LOCATION=025   CHF   INPUTS=CA(3=1)
LOCATION=027   SH   INPUTS=CHA,CHF
LOCATION=047   DD   INPUTS=SH
LOCATION=045   FB   INPUTS=DD
LOCATION=065   VE   INPUTS=FB,GR,TD
LOCATION=067   GR
LOCATION=063   TD
END OF MODEL
PRINT
```

Table 6-8

ANALYSIS COMMANDS FOR THE D.C. SHUNT MACHINE DRIVE TRAIN

```
TITLE=SHUNT MACHINE DRIVE TRAIN -- DEFAULT CONTROLLER
PARAMETER VALUES
   IR CHF=20.
   S  TD=4.
OUTRATE=1.
PRINTER PLOTS
   PRINT CONTROL=3     TMAX=122.     TINC=0.5
DISPLAY1,PV1VE,VS,TIME
         VV1VE,VS,TIME
         I1 CA,VS,TIME
         T2 SH,VS,TIME
         AH BA,VS,TIME
DISPLAY2,VR3SH,VS,TIME
         VR1SH,VS,TIME
SIMULATE
```

6.5 D.C. Shunt Machine Drive Train with Armature Chopper Bypass

This model represents the GE/Chrysler ETV1 vehicle. It was used as an example in Section 4.0 of this report. Notice that specific connections are required only to override the default connections for the two interfaces involved. All other connections continue to be made by default. Also notice that this is the first example for which more than one page of schematic is necessary. The schematic of the logic is useful for model verification but does not resemble a hand-drawn logic sketch. In most cases, it is impossible to arrange the HEAVY schematic for logic to satisfactorily reproduce a sketch made to design the logic.

Table 6-9

MODEL GENERATION COMMANDS TO DEFINE THE ETV1

```
MODEL DESCRIPTION=ETV1 DRIVETRAIN, VEHICLE, CONTROLLER
LOCATION=002   BA
LOCATION=032   CA    INPUTS=BA,SW1(VO1=I,2)
LOCATION=042   SW1   INPUTS=CHA(I,1=VA1),SH(I,1=VB1),LO(TRU=SWI)
LOCATION=075   CHA   INPUTS=CA(2=1),SW2(VO1=I,2),SH(VR,1=VR,2)
LOCATION=037   CHF   INPUTS=CA(3=1)
LOCATION=057   SW2   INPUTS=SH(I,1=VA1),LO(TRU=SWI)
LOCATION=014   SW3   INPUTS=CHA(V,2=VA1),CA(V,2=VB1),LO(TRU=SWI)
LOCATION=134   LO    INPUTS=LC(TRU=L1),LC1(TRU=L2)
LOCATION=132   LC1   INPUTS=SH(VR,1=L1)
LOCATION=102   LC    INPUTS=CHA(DC=L1)
LOCATION=019   SH    INPUTS=SW3(VO1=V,1),CHF(2=3),CHA(RE=RE)
LOCATION=161   DD    INPUTS=SH
LOCATION=163   FB    INPUTS=DD
LOCATION=165   VE    INPUTS=FB,PD
LOCATION=167   PD
LOCATION=105   WE
LOCATION=107   EC
END OF MODEL
```

Table 6-10

ANALYSIS COMMAND FOR THE ETV1 SIMULATION

```
TITLE=ETV1 DRIVE TRAIN, VEHICLE AND CONTROLLER
PARAMETER VALUES
IR CHF=20.,D  DD=5.48
L2 LC1=96,L2 LC=0.95,VB1SW2=0.
S  PD=0.

TABLE=VC PD(50)
 0.     1.     2.     3.     4.     5.
 6.     7.     8.     9.    10.    11.
12.    13.    14.    15.    16.    17.
18.    19.    20.    21.    22.    23.
24.    25.    26.    27.    28.    78.
79.    80.    81.    82.    83.    84.
85.    86.    87.    88.    89.    90.
91.    92.    93.    94.    95.    96.
97.   122.
00.00  01.14  02.29  03.43  04.58  05.72
06.87  07.95  08.98  09.94  10.85  11.71
12.52  13.29  14.01  14.69  15.32  15.91
16.47  16.99  17.48  17.92  18.33  18.71
19.05  19.36  19.64  19.89  20.10  20.10
19.46  18.92  18.48  18.06  17.67  17.31
16.99  15.57  14.16  12.74  11.32  09.91
08.49  07.08  05.66  04.25  02.83  01.42
00.00  00.00
```

```
PRINT CONTROL=5.
DEFINE STATES
6=POSIT,7=VELOC
DEFINE RATES   7=ACCEL
DEFINE VARIABLES
14=AMPS,40=TORQUE,24=FIELDV,16=ARM V,
59=SHAFTW,2=AMPHRS

PRINT VARIABLES=POSIT,VELOC,ACCEL,TORQUE,
                AMPHRS,AMPS
DISPLAY1,VELOC,VS,TIME
         VC2PD,VS,TIME
DISPLAY2,AMPS,VS,TIME
         AMPHRS,VS,TIME
DISPLAY3,EF SH,VS,TIME
DISPLAY4,EF DD,VS,TIME
DISPLAY5,EF CHA,VS,TIME
DISPLAY6,T2 SH,VS,TIME
PRINTER PLOTS
OUTRATE=2.
TMAX=122.
TINC=0.5
SIMULATE
```

6.6 D.C. Shunt Machine Drive Train with Battery Switching

In this modified representation of the GE/Chrysler ETV1, the armature circuit chopper has been replaced by a battery switch which will connect the four batteries in various series/parallel combination to provide a stepped terminal voltage. The shunt field machine is forced into field control mode at all times. Terminal voltage is stepped as a function of vehicle speed.

The output of SWitch 2 is used as the control input to the battery switch. This output, which may be 1, 2, or 4, sets the number of batteries to be in series in each leg of the series/parallel set. Notice that the field circuit chopper is connected through a current accumulator to only one of the four batteries so it receives a constant terminal voltage.

Table 6-11

MODEL GENERATION COMMANDS FOR THE D.C. SHUNT
MACHINE DRIVE TRAIN WITH BATTERY SWITCHING

```
MODEL DESCRIPTION=GE VEH BATTERY SWITCH
LOCATION=001,BA1
LOCATION=003,CA      INPUTS=BA1
LOCATION=021,BA2
LOCATION=031,BA3
LOCATION=052,BA4
LOCATION=033,BS      INPUTS=CA(2=1),BA2,BA3,BA4,SW2(VO1=NS)
LOCATION=007,CHF     INPUTS=CA(3=1)
LOCATION=037,SH      INPUTS=BS(2=1),CHF(2=3)
LOCATION=039,DD      INPUTS=SH
LOCATION=059,FB      INPUTS=DD
LOCATION=079,VE      INPUTS=FB,TD
LOCATION=077,TD
LOCATION=071,WE
LOCATION=072,EC
LOCATION=123,LC1     INPUTS=DD(W,1=L2)
LOCATION=163,LC2     INPUTS=DD(W,1=L2)
LOCATION=137,SW1     INPUTS=LC1(FAL=SWI)
LOCATION=159,SW2     INPUTS=LC2(FAL=SWI),SW1(VO1=VA1)
END OF MODEL
PRINT
```

Table 6-12

ANALYSIS COMMANDS FOR THE D.C. SHUNT
MACHINE DRIVE TRAIN WITH BATTERY SWITCHING

```
TITLE=GE VEH BATTERY SWITCH
OUTRATE=1.
PARAMETER VALUES
CYCLES=10     IR CHF=20       D  DD=5.4     S  TD=4.
M  SH=2.      NB BS=4         VA1SW1=1.       VB1SW1=2.
VB1SW2=4.     NC BA1=12       NC BA2=12       NC BA3=12
NC BA4=12     L1 LC1=108.09   L1 LC2=216.18
RF SH=2.4     IM SH=600.      VFRSH=24.
PRINTER PLOTS
DISPLAY1,PV1VE,VS,TIME
         VV1VE,VS,TIME
         I1 CA,VS,TIME
          T2 SH,VS,TIME
         AH BA,VS,TIME
DISPLAY2,VR3SH,VS,TIME
         VR1SH,VS,TIME
PRINT CONTROL=3      TMAX=122     TINC=.25
SIMULATE
```

6.7 Flywheel/Heat Engine Parallel Hybrid Drive Train

This model represents a hybrid with an extremely simple control strategy. The flywheel accelerates the car from rest to a specified speed, then the heat engine is clutched in to provide power at higher speeds. The flywheel is declutched when the heat engine is clutched in. The transition point corresponds roughly to the idle speed of the heat engine. Naturally, this simple strategy does not yield very good performance because of the limited acceleration possible with the heat engine alone, nor does it provide good regeneration to the flywheel since it only regenerates at speeds below the transition point. Moreover, the two clutches chatter somewhat at the transition between flywheel and heat engine model. The problem could be alleviated by declutching the flywheel at a slightly higher speed than that at which the heat engine is clutched in.

The clutch logic and CVT ratio logic for this model could be the subject of much analysis.

Table 6-13

MODEL GENERATION COMMANDS FOR THE FLYWHEEL/HEAT ENGINE PARALLEL HYBRID DRIVE TRAIN

```
MODEL DESCRIPTION=FLYWHEEL/HEAT ENGINE HYBRID
LOCATION=32,FL
LOCATION=12,CL1,INPUTS=FL,LA(FAL=E)
LOCATION=16,CT1, INPUTS=CL1
LOCATION=34,HE
LOCATION=36,CL2,INPUTS=HE,LA(TRU=E)
LOCATION=38,SU,INPUTS=CT1,CL2,SW(VO1=PR,1)
LOCATION=138   SW    INPUTS=LA(TRU=SWI)
LOCATION=136   LA    INPUTS=SW2(VO1=L1)
LOCATION=134   SW2    INPUTS=LC1(TRU=VA1,FAL=VB1),LC2(TRU=SWI)
LOCATION=112   LC1    INPUTS=VE(VV,1=L1)
LOCATION=132   LC2    INPUTS=CT2(TR,1=L2)
LOCATION=40,CT2,INPUTS=SU
LOCATION=60,DD,INPUTS=CT2
LOCATION=58,FB,INPUTS=DD
LOCATION=56,VE,INPUTS=FB,TD
LOCATION=54,TD
END OF MODEL
PRINT
```

Table 6-14

ANALYSIS COMMANDS FOR THE FLYWHEEL/HEAT ENGINE PARALLEL HYBRID DRIVE TRAIN

```
TITLE = FLYWHEEL/HEAT ENGINE HYBRID
PRINT CONTROL=3.
PARAMETER VALUES
     RL CT1=4.2, RH CT1=70., RL CT2=4.2, RH CT2=70.
S  TD=4.
R  CT1=4.2,R  CT2=4.2
WO FL=2200.,  WO HE=150.
S  HE=3.
   L1 LC2=0.,  L2 LC1=5.,  L2 LA=1.,  VA1SW=1.,  VB1SW=3.
   PR3SU=2., PR4SU=0., PR5SU=0.
TMAX=10.
TINC=.25
PRINTER PLOTS
DISPLAY1,PV1VE,VS,TIME
VV1VE,VS,TIME
T2 SU,VS,TIME
T2 FL,VS,TIME
T2 HE,VS,TIME
SIMULATE
```

6.8 Electric/Heat Engine Series Hybrid Drive Train

The motor-generator set is represented by the heat engine/shunt machine leg of the hybrid. Inputs to the SUmmer at location 029 set the operating speed and torque of the motor-generator. Current from the shunt machine is summed with drive train current at the current accumulator at location 023. The drive train itself is a simple d.c. series machine followed by a reduction gear and a manual transmission.

The parameter values given in the HEAVY simulation commands which follow are by no means carefully selected. Careful analysis could result in a hybrid in which, for example, the current from the generator matched the drive train requirements at a specified cruise speed.

Table 6-15

MODEL GENERATION COMMANDS FOR THE ELECTRIC/HEAT ENGINE SERIES HYBRID DRIVE TRAIN

```
MODEL DESCRIPTION=SERIES HYBRID
LOCATION=005,HE
LOCATION=007,CL     INPUTS=HE
LOCATION=009,FGH    INPUTS=CL
LOCATION=021,BA
LOCATION=023,CA     INPUTS=BA
LOCATION=044,CHF    INPUTS=CA(3=1)
LOCATION=025,SH     INPUTS=CA(2=1),CHF(2=3),FGE(W,1=W,2),
                         FGE(JD,1=JD,2),FGE(WD,1=WD,2)
LOCATION=027,FGE    INPUTS=SH(T,2=T,1),SH(JU,2=JU,1),SH(WX,2=WX,1)
LOCATION=029,SU     INPUTS=FGH(2=1),FGE(2=3)
LOCATION=063,CHS    INPUTS=CA(4=1)
LOCATION=065,SE     INPUTS=CHS
LOCATION=067,FGS    INPUTS=SE
LOCATION=070,FT     INPUTS=FGS
LOCATION=050,FB     INPUTS=FT
LOCATION=048,VE     INPUTS=FB,TD
LOCATION=046,TD
END OF MODEL
PRINT
```

Table 6-16

ANALYSIS COMMANDS FOR THE ELECTRIC/HEAT ENGINE SERIES HYBRID DRIVE TRAIN

```
TITLE=SERIES HYBRID
PARAMETER VALUES
   R  FGH=2.
   R  FGE=5.
   R  FGS=4.
   PR1SU=1., PR3SU=2.,TR2SU=100.,W2 SU=250.
   WD2SU=0., CE2SU=0., JD2SU=0.1
   TR2SH=-25.
   S  TD=4.
TMAX=10.,TINC=.25,PRINT CONTROL=3.
SIMULATE
```

6.9 Electric/Heat Engine Parallel Hybrid Drive Train

This is the first step in development of the configuration described in Section 5.0 of this report.

This model represents the drive train, but not the energy management logic, of a vehicle conceptually designed by AiResearch, reference 3. Torque from a synchronous electric machine and from a heat engine are summed to drive the vehicle. A CVT controller at location 048 attempts to set the CVT ratio to allow the heat engine to run at a specified speed. In this simplified model, the electric machine accelerates the vehicle from rest to about 3 km/h and then the heat engine drives the car above that speed.

Table 6-17

MODEL GENERATION COMMANDS FOR THE ELECTRIC/HEAT ENGINE PARALLEL HYBRID DRIVE TRAIN

```
MODEL    DESCRIPTION=GARRETT/AIRESEARCH    HYBRID    WITH    SIMPLE
CONTROLLER
LOCATION=001,BA
LOCATION=003,IV     INPUTS=BA
LOCATION=005,EM     INPUTS=IV
LOCATION=007,FGE    INPUTS=EM
LOCATION=021,HE
LOCAITON=023,CL     INPUTS=HE,LC(TRU=E)
LOCATION=025,FGH    INPUTS=CL
LOCATION=030,SU     INPUTS=FGE,FGH,SW(VO1=PR,3)
LOCATION=045,LC     INPUTS=VE(VV,1=L1)
LOCATION=047,SW     INPUTS=LC(TRU=SWI)
LOCATION=050,CT     INPUTS=SU,CC(RC=RC)
LOCATION=048,CC     INPUTS=DD
LOCATION=070,DD     INPUTS=CT
LOCATION=077,FB     INPUTS=DD
LOCATION=075,VE     INPUTS=FB,TD
LOCATION=073,TD
LOCATION=041,WE
LOCATION=061,EC
END OF MODEL
PRINT
```

Table 6-18

ANALYSIS COMMANDS FOR THE ELECTRIC/HEAT ENGINE PARALLEL HYBRID DRIVE TRAIN

```
TITLE=GARRETT/AIRESEARCH HYBRID WITH SIMPLE CONTROLLER
PARAMETER VALUES
    WI HE=199., WI EM=12., WI IV=36., WI CT=167., WI DD=0.
    WC BA=7.149, WTOVE=2032.
    C  HE=410., C  EM=375., C  IV=905., C  CT=520., C  DD=0.
    CC BA=1004.
    R  FGE=4., R  FGH=3., D  DD=3.
    PR1SU=2., PR4SU=0., PR5SU=0.
    WC CC=50., RL CC=0.3, RH CC=3.
    WO HE=100., SF CL=.2
    S  HE=4., TX HE=154.3
    S  TD=4.
    VA1SW=3., VB1SW=1., L2 LC=0.833
PRINTER PLOTS
PRINT CONTROL=3., TINC=.25, TMAX=122.
PRATE=4.
DISPLAY1
   VV1VE,VS,TIME
   T2 FGE,VS,TIME
   T2 CL,VS,TIME
   T2 SU,VS,TIME
SIMULATE
```

6.10 Electric/Heat Engine Parallel Hybrid Drive Train with Energy Management Logic

This is the drive train described in Section 5.0 of this report. It is repeated here for reference. This model represents the drivetrain and energy management logic of the vehicle conceptually designed by AiResearch, reference 3.

Table 6-19

MODEL GENERATION COMMANDS FOR THE ELECTRIC/HEAT ENGINE PARALLEL HYBRID DRIVE TRAIN WITH ENERGY MANAGEMENT LOGIC

```
MODEL DESCRIPTION=GARRETT/AIRESEARCH HYBRID-ELECTRIC VEHICLE
LOCATION=21      BA
LOCATION=01      IV      INPUTS=BA
LOCATION=03      EM      INPUTS=IV
LOCATION=23      FGE     INPUTS=EM
LOCATION=07      HE
LOCATION=05      CL      INPUTS=HE,LOE(TRU=E)
LOCATION=25      SU      INPUTS=FGE,CL,LAS(FAL=PR,1),LOE(TRU=PR,3)
LOCATION=110     LOE     INPUTS=LAE(TRU=L1),LAS(TRU=L2)
LOCATION=130     LAE     INPUTS=LAA(TRU=L1),LC3(TRU=L2)
LOCATION=108     LAS     INPUTS=LAC(TRU=L1),LC5(FAL=L2)
LOCATION=144     LAA     INPUTS=LC1(FAL=L1),LC4(FAL=L2)
LOCATION=148     LAC     INPUTS=LC1(TRU=L1),LC2(TRU=L2),LC3(TRU=L3)
LOCATION=106     LC5     INPUTS=BA(ST,2=L1)
LOCATION=142     LC4     INPUTS=TD(VCS=L2)
LOCATION=150     LC3     INPUTS=VE(VV,1=L1)
LOCATION=168     LC2     INPUTS=TD(VC,2=L1,VCS=L2)
LOCATION=146     LC1     INPUTS=TD(VCS=L1,VC,2=L2)
LOCATION=27      CT      INPUTS=SU,CC(RC=RC)
LOCATION=47      CC      INPUTS=FG(W,1=W,2)
LOCATION=49      FG      INPUTS=CT
LOCATION=69      DD      INPUTS=FG
LOCATION=67      FB      INPUTS=DD
LOCATION=65      VE      INPUTS=FB,TD
LOCATION=63      TD
LOCATION=41      WE
LOCATION=51      PC
LOCATION=61      EC
END OF MODEL
PRINT
```

Table 6-20

ANALYSIS COMMANDS FOR THE ELECTRIC/HEAT ENGINE PARALLEL HYBRID DRIVE TRAIN WITH ENERGY MANAGEMENT LOGIC

```
TITLE=GARRETT/AIRESEARCH HYBRID
PARAMETER VALUES
     L2 LC3=0.833, L1 LC4=-1., L2 LC5=0.5
     WO HE=110.
     WF1SU=.3, WF3SU=.7
     S  IV=1.
     WI CL=0., WI HE=199., WI EM=12., WI IV=36., WI DD=59.
     WC BA=4.6
     R  FGE=3.5, R  FG=12., D  DD=1.
     WC CC=300., RL CC=0.3, RH CC=3.
     S  HE=4., TX HE=154.3
     S  TD=4.
     PR4SU=0., PR5SU=0.
     JI HE=.03, JI FGE=0., JI CT=0., JI FG=0., JI DD=0., JI FB=0.
     CA BA=393.2, NC BA=84.
     RT EM=13.6
     RP CT=90000., RT CT=215.
     WI FG=0.
     RP DD=90000., RT DD=774.
PRINTER PLOTS
PRINT CONTROL=3., TINC=.5, TMAX=122.
OUTRATE=1.    PRATE=1.
DISPLAY1
     VV1VE,VS,TIME
DISPLAY2
     T2 CL,VS,TIME
     T2 FGE,VS,TIME
SIMULATE
```

7.0 REFERENCES

1. Hammond, R. A., and McGehee, R. K., "Users's Guide to the Hybrid and Electric Advanced Vehicle Systems (HEAVY) Simulation," NASA Contract DEN3-151, September 1981.

2. Schwartz, Harvey L., and Gordan, Andrew L., "Impact of Propulsion System R&D on Electric Vehicle Performance and Cost," DOE/NASA/1049-9, NASA TM-81548.

3. Norrup, L. V., and Lintz, A. T., "Advanced Propulsion System for Hybrid Vehicles," DOE/NASA/0091-80-1, January 1980.

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